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Natural convection cooling of a three-by-three array of leadless chip carrier packages in a dielectric liquid

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THESIS

NATURAL CONVECTION COOLING OF A THREE BY THREE ARRAY OF LEADLESS CHIP CARRIER PACKAGES IN A DIELECTRIC LIQUID

by

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NATURAL CONVECTION COOLING OF A THREE-BY-THREE ARRAY OF LEADLESS CHIP CARRIER PACKAGES IN A DIELECTRIC LIQUID

by

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ABSTRACT

Liquid cooling of a three-by-three array of commercially available leadless chip carrier packages, mounted on a ceramic substrate was examined. Baseline data were obtained for cooling with pure dielectric liquids. The effects of addition of high thermal conductivity ceramic powder to the liquid were next examined, both for natural and forced circulation conditions. Vertical and horizontal orientations were studied, for two different ceramic particle types, and two different particle sizes for each ceramic. For a range of chip power levels, chip, substrate and cold plate temperatures were measured. Interpretations for these data are provided. A numerical model was developed for the vertical geometry and compared to the measurements obtained.

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The people who contributed to this thesis enabled it to be completed in a timely manner. They include Jim Scholfield, who repeatedly provided workable solutions to difficult technical problems, and whose ability to produce equipment in the blink of an eye without significant funds is truly amazing. Mr. Tom McChord was instrumental in taking rough plans and directing the production of the enclosure. Lastly, I would like to thank Professor Joshi for continuing as my thesis advisor, even though he left the school 8 months ago. His advice and direction enabled a siginficant amount of work to be accomplished.

I. INTRODUCTION

A. STATEMENT OF PROBLEM

As the demand for faster yet smaller computers has grown, one physical limitation has been the heat removal capacity from the system. The search for effective thermal management techniques has expanded in recent years and is expected to continue as long as package sizes decrease and clock speeds increase. These two factors combine to dramatically increase the heat flux seen by the package.

Historically, there has been a progression in the heat removal capacity that has matched or only slightly trailed the increase in the heat generation rate. Thus, thermal considerations have generally had a secondary effect in slowing the quest for greater computational speed and reduced package size. Today, though, the heat fluxes exceed 65 watts/cm^2 and the capability to remove this heat flux is sorely challenged. Bar-Cohen [Ref. 1]

Natural circulation air cooling was one of the first methods used to remove heat. The advantages are obvious, air is virtually free and is usually found in abundance. However, for higher heat loads and for applications with concern for airborne contaminant damage, natural convection may not be adequate or appropriate. Forced convection air cooling can provide increased heat removal capability. For many applications the pressure drop due to filtering is within acceptable ranges. Sloan [Ref. 2]

Mezenq et.al. [Ref. 3] studied gas fluidized beds to improve heat transfer capability. They demonstrated dramatic performance increases (heat transfer coefficient increase) by the use of small suspended sand or silica particles in an air stream. The bed exhibited a very high effective thermal conductivity with low dependence on particle conductivity.

Situations arise, where either due to the heat load, or the environment, air is not a suitable candidate as the primary heat sink. A number of techniques are currently being investigated for such applications. They include conduction with indirect liquid cooling, use of fluid backplane and direct liquid immersion cooling.

One approach is the use of thermally conductive solids to transfer the heat to a cold fluid as exemplified by the water cooled piston structure of the IBM Thermal Conduction Module. A lower liquid side thermal resistance can be achieved by utilizing a highly finned silicon or ceramic heat exchanger. The interface resistance between the chip or package surface and the primary conductor poses the primary limitation on the thermal performance. Bergles and Bar Cohen [Ref. 4]

A second approach is the use of a fluid backplane. This can reduce the interfacial resistance between the chip and the coolant. The resistance can be entirely eliminated by making the cold plate an integral part of the module. Kishimoto and Osaki [Ref. 5]

A third approach is the use of direct immersion cooling. Here, the electronic components are immersed in a dielectric liquid. Heat transfer in these situations can be either single phase or with a phase change. The coolant flow may be either natural or forced. Various fluorocarbon liquids available as Fluorinerts® (3M Corporation) have

been used in this application. Another variation is the use of mixtures of phase change particles and dielectric liquids to improve the heat transfer capabilities of the pure fluid; Choi, et.al. [Ref. 6].

B. PREVIOUS RESEARCH IN IMMERSION COOLING

The conduction interfacial resistance at the chip or package places an upper bound on the attainable thermal performance of methods involving indirect liquid cooling. Baker [Ref. 7] outlined the fundamentals of immersion cooling and reported the results of a study using Freon - 113 and Dow Corning #200 silicone dielectric liquid to effectively cool small heat sources. Immersion cooling is currently commercially implemented in the Cray-2 supercomputer; Danielson, et. al. [Ref. 8.]. Other geometries have been investigated. One possible design is a liquid encapsulated module, similar to that studied by IBM. In this design, natural convection heat transfer carries the heat dissipated from the immersed chips to a perfluorinated liquid and eventually to the enclosure walls; Bergles and Bar Cohen [Ref. 4]. Related concepts involve pool boiling at the chips investigated by Arata [Ref. 9] and/or condensation at the enclosure walls.

A number of studies of natural convection in geometries of interest to electronic cooling have recently been carried out. Joshi et.al. [Ref. 10] presented flow visualizations and component surface temperature measurements for natural convection cooling of a three by three array of discrete heated protrusions on the vertical wall of a rectangular enclosure filled with a dielectric liquid. Joshi et.al. [Ref. 11] presented experimental

studies of the heat transfer and flow characteristics of a column of protruding heat sources on a vertical surface and within a vertical channel. Sathe and Joshi [Ref. 12] reported results of a two-dimensional numerical investigation of natural convection flow and heat transfer arising from a protruding heat source on a vertical plate within an enclosure. Joshi and Paje [Ref. 13] reported experimental results of natural convection heat transfer from a commercially available leadless chip carrier package. Wroblewski and Joshi [Ref. 14] reported the results of a numerical investigation of the same leadless chip carrier package studied by Joshi and Paje.

The thermal properties of four Fluorinerts and water are shown in Table 1-1. Reference to Table 1-1 reveals these Fluorinerts to have low thermal conductivities, specific heats and latent heats of vaporization compared to water. The direct liquid cooling of electronic components necessitates the use of chemically stable and inert, non-toxic liquids with high dielectric strength and high volumetric resistivity. The need for a fluid suitable for electronic circuit applications has constrained the choices to fluids which have poor thermal transport characteristics. The desire to improve the transport properties led to this study. It examines the effect of particle additions to the Fluorinert liquids on their heat transfer characteristics. Also presented are measurements and numerical simulation of natural convection in pure liquids.

TABLE 1-1: THERMOPHYSICAL PROPERTIES OF SEVERAL LIQUIDS AT ATMOSPHERIC PRESSURE (3M MANUAL) [REF. 15]

	Perfluorinated Liquid Designation				
Property	FC-87	FC-72	FC-84	FC-75	Water
Boiling Point, degrees C	30	56	83	100	100
Liquid Density, ρ_l, kg/m3	1633	1680	1575	1590	958
Kinematic Viscosity, ν, cs	4.20E-04	0.4	0.55	4.5E-04	2.70E-04
Specific Heat. c. J/kg K	1088	1088	1130	1172	4184
Thermal Conductivity, k, W/mK	5.51E-02	5.45E-02	5.35E-02	5.70E-02	6.83E-01
Vol. Coef. Expansion, β, K^{-1}	1.60E-03	1.60E-03	1.50E-03	1.40E-03	2.00E-04
Dielectric Constant	1.71	1.72	1.71	1.75	78.00
Average molecular weight, g/mole	288	338	388	438	18

C. OBJECTIVES

The investigation reported here is a continuation of the studies conducted by Joshi et. al. [Ref. 10, 11], Sathe and Joshi [Ref. 12], Joshi and Paje [Ref. 13] and Wroblewski and Joshi [Ref. 14]. The present study was conducted with a three by three array of leadless chip carrier packages mounted on a ceramic substrate which formed one wall of a dielectric liquid filled enclosure. The first part investigated the effect of various ceramic particle loadings on overall heat transfer rates in two orientations, the (i) horizontal and (ii) vertical. Ceramics, particularly the nitrides, are a class of materials that combine many useful features. They have very high electrical resistivities, moderate densities and have exceptionally high thermal conductivities. Table 1-2 shows the properties of some

ceramics that were considered for this study. The present investigation studied the effect of powdered Boron Nitride (BN) and Aluminum Nitride (AlN) additions on the thermal transport characteristics of Fluorinert-75 (FC 75). During the course of the investigation, no enhancements were noted in the heat transfer rates as a result of the particle additions. Extensive measurements of heat transfer characteristics were made for various particle sizes and volume fractions. The horizontal geometry was tested in natural circulation, natural circulation with external vibration, and forced circulation modes. The vertical geometry was only tested in the natural circulation mode.

TABLE 1-2: CERAMIC PROPERTIES

Property	Aluminum Nitride (AlN)	Boron Nitride (BN)	Alumina Al_2O_3	Magnesia MgO	Silicon Nitride (Si_3N_4)
Density, ρ, kg/m3	3050[$]	2290[#]	3970[+]	3580[+]	3440[+]
Thermal Conductivity, k, W/m K	320[*]	225[*]	30[+]	48[+]	16 - 33[+]
Electrical Resistivity Ω - m	>10E12[+]	>10E12[#]	>10E12[+]	>10E12[+]	>10E12[+]

[$] Samsonov [Ref. 16], * Slack [Ref. 17], [+] Callister [Ref. 18], [#] Mutterties [Ref. 19]

The second part of the study was the modification and use of a numerical model to simulate the three dimensional transport for the pure liquid conditions with a vertical orientation of the substrate.

The specific objectives were:

- To design and build an enclosure to study natural convection from a three by three package array in fluorocarbon liquids.
- To study the effects of component orientation on the overall heat transfer rates in the enclosure under natural convection conditions.

- To design and build an enclosure in order to study forced convection from the above package array in fluorocarbon liquids.
- To investigate heat transfer in liquid--ceramic mixtures for several ceramic types, particle sizes and volume fractions.
- To develop a numerical model of the nine package vertical substrate orientation.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

As shown in Figure 2-1, the experimental apparatus consisted of several components; an enclosure containing the electronic packages, a power distribution system, a heat removal system, and a data acquisition system. For the forced circulation flow data, a screw type pump, a turbine flow meter and associated tubing were added to the apparatus. Figure 2-2 is a photograph of the enclosure interior.

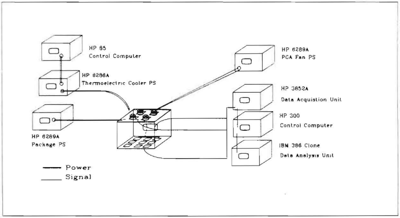

Figure 2-1: System arrangement and apparatus.

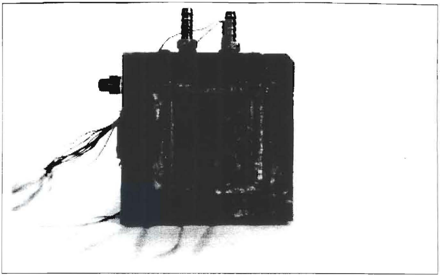

Figure 2-2: Photograph of enclosure interior.

A. APPARATUS FOR NATURAL CONVECTION TESTS

The enclosure consisted of four side walls of 2.5 cm thick Plexiglas plates, with an outside dimension of 9.86 cm by 9.92 cm, a bottom wall of 2.5 cm thick Plexiglas, and an aluminum cover plate 9.96 cm by 9.96 cm and 0.66 cm thick. Both the enclosure and the plate had a reference chamfer cut in the front right corner to permit retention of the proper alignment of the enclosure and plate. The interior of the enclosure initially measured 5.18 cm by 5.12 cm by 5.08 cm deep. Figure 2-3 shows an overhead view of the interior of the enclosure.

The rear wall was provided with a 9 pin connector to provide a data and power path to the package assembly. A ceramic plate 5.08 cm by 5.08 cm by 0.05 cm thick was

inserted to protect the leads and to prevent flow disturbances caused by the wires. The ceramic plate reduced the interior to 4.72 cm by 5.08 cm by 5.08 cm deep. A recessed channel with a 3 mm diameter gasket was provided in the top of the side walls. The rear wall also had a 0.64 cm hole drilled to provide a vent/expansion path. A 0.64 cm I.D. tygon tube was attached to provide a surge volume during the heating cycle. Figure 2-4 shows the enclosure section view, cut through the middle row of packages. Additionally, a form fitting 2.54 cm thick insulation pad, which is not shown, surrounded the enclosure during operation.

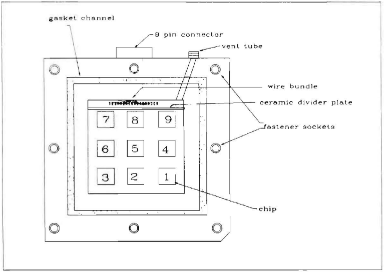

Figure 2-3: Plan view, enclosure interior, cover removed.

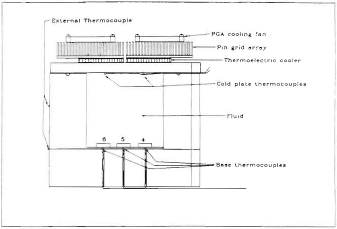

Figure 2-4: Section view, enclosure midplane.

Most of the power generated by the package was removed from the enclosure by the aluminum cover plate. Eight 0.64 cm holes were drilled and tapped to provide a means of attaching the plate to the enclosure. Four thermoelectric (Peltier effect) coolers were mounted to the top of the aluminum plate to remove the heat produced by the electronic packages. The four coolers were in turn cooled by four Pin Grid Arrays (PGA) with integral cooling fans. The four coolers were powered by a HP 6286 DC Power Supply under control of a HP 85B micro computer. The coolers were controlled to maintain a temperature of 24 °C on the lower face of the aluminum plate. This temperature was monitored by four copper-constantan thermocouples. The Pin Grid Array cooling fans were also controlled by a HP 6289A DC Power Supply. These Pin Grid Arrays and their

associated fans are normally installed in computers utilizing Intel 486 chips and were operated in a similar manner.

The electronic packages formed a three by three array of leadless chip carriers mounted on a ceramic substrate. The ceramic substrate of 5.18 cm length, 5.06 cm width and a thickness of 0.07 cm, was mounted horizontally at the base of the enclosure. Five of the nine packages were equipped with diode type temperature sensors integrated within the chips. These diodes display a linear decrease in resistance with temperature increase. Only three of the five diodes were monitored due to space limitations. Like any solid state component, the diodes are limited in their range of temperature. The manufacturer (Texas Instruments) indicated a maximum of 135°C, and no data was acquired above this temperature. The temperature sensors are mounted on the base of the package. The chip is covered by a thin, brass lid. Between the chip and the lid a small air gap exists. The nine chips within the package array could be wired in a wide variety of configurations. Due to space considerations, all nine chips were wired in parallel. The wire gage limited the total current to 1 amp DC. This proved to be sufficient during these trials and exceeded the heat removal capacity of the cooling medium.

Attached to the bottom surface of the ceramic substrate, under each package was a 0.127 mm diameter copper-constantan thermocouple. These thermocouples were calibrated at the same time as the internal diodes in a temperature controlled bath against a platinum resistance thermometer. Four 0.127 mm copper-constantan thermocouples were attached to the bottom of the aluminum plate. An additional 0.127 mm copper-constantan

thermocouple monitored the temperature of the thermoelectric coolers to prevent damage to the coolers. Two thermocouples were mounted on one enclosure outside wall to assist in determining steady state conditions. Ambient temperature was also monitored.

B. STUDIES WITH EXTERNAL EXCITATION

As will be discussed later, the ceramic particles, especially the Aluminum Nitride, were denser than the Fluorinert, and were not able to be picked up by the buoyant stream. In an effort to keep them from settling on the substrate, an external excitation was provided via an eccentric weight attached to a DC motor via a common bed plate to the enclosure. No other modifications to the enclosure were made for these data runs.

C. MODIFICATIONS FOR FORCED CONVECTION

For the forced circulation portion of the study, a flow loop was constructed to enable fluid to be circulated through the enclosure as illustrated in Figure 2-5 and 2-6. Four 0.64 cm diameter holes were drilled through the right wall of the enclosure used for the natural circulation study. The holes were arranged with two in the lower portion of the wall and two in the upper portion. A divider plate was inserted within the enclosure so as to allow the fluid entering at the lower two holes to flow over the package, up through three holes drilled in the plate to the upper portion of the enclosure, past the cold plate, to the suction of a positive displacement screw type pump, through a turbine flowmeter and return to the enclosure. A hose clamp was applied to the vent line, to prevent leakage.

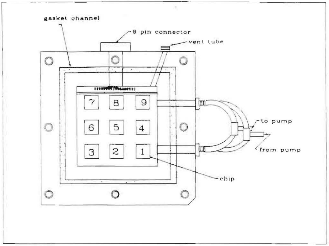

Figure 2-5: Plan view, enclosure interior, cover removed, flow path illustrated.

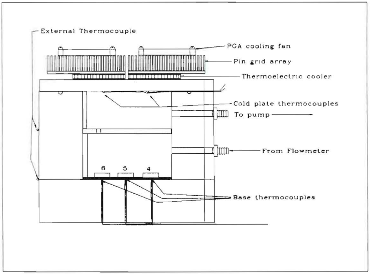

Figure 2-6: Section view, enclosure midplane, flow path illustrated.

D. POWER DISTRIBUTION SYSTEM

Power to the package resistors was supplied by a 0-1.5 A, 0-40 V HP-6289A DC Power Supply. As discussed above, the individual packages were wired in parallel. The data acquisition system was connected to read the voltage drop across the nine packages and also across a known precision resistor that was wired in series with the package assembly. From these two voltages, the input power to the chipset using the following relation:

$$\text{Power} = \frac{V_{\text{resistor}}}{R} * V_{\text{package}}$$

E. DATA ACQUISITION ASSEMBLY

The data acquisition assembly consisted of a HP 300 computer system, a HP-3852 Data Acquisition Unit and a 386 clone PC. The HP-300 computer instructed the data acquisition system to monitor voltages, resistance and temperatures from the desired elements. A monitoring program determined when steady state had been achieved and alerted the operator. The monitoring program also detected out of limit parameters, similarly alerting the operator to take corrective action. When steady state, as indicated by a less than 0.2 °C change in temperatures, on the aluminum plate, was achieved, a separate data collection program was run which directed the data to the 386 computer where it could be analyzed. Following evaluation of a successful data run, the monitoring program was reloaded and the next set of conditions established. For the forced circulation data, an Omega Engineering, Inc. FLSC-18B turbine flowmeter was used to

measure the flowrate. The flowmeter was calibrated using FC-75 in the range 51 to 117 ml/s.

F. EXPERIMENTAL PROCEDURE

The study examined two different geometries, four different fluid/ceramic mixtures, as many as thirteen different ceramic particle loads per ceramic and up to five power levels per ceramic powder load, without exceeding the maximum chip temperature of 135 °C. To prepare for each run, the same basic procedure was followed. The enclosure was filled with FC - 75, and the ceramic load was adjusted as necessary. After reassembling the cover and vent, the Pin Grid Arrays were placed on the top of the Peltier effect coolers. The monitoring system and all auxiliary power systems were started. The monitoring program was used during heatup, to check on system performance and to evaluate proximity to steady state. During the heatup, dissolved air was vented from the assembly, and no data was taken until this was complete. A series of runs was defined as a set of runs at power levels decreasing from the highest chosen for the given conditions; up to a maximum of five power levels for each ceramic load. The natural circulation and external excitation runs all started at 1.55 watts per chip (14 watts total to array) or the highest achievable power level and included data at 1.39, 1.22, 1.05 and 0.89 watts per package. The forced circulation series all started at 2.2 watts per chip (20 watts total to the array), and included data at 1.55 and 0.9 watts per chip.

1. Natural Circulation Runs

Once the monitoring program indicated that steady state had been achieved, the data collection program (see Appendix A) was loaded. No adjustments were permitted during data collection to the input power or thermoelectric cooler voltage. Three data runs were generally taken for each condition. If the plate temperature or input power varied outside of the specified band during the data runs, the collection program was unloaded, and the monitoring program was reloaded to restore steady state. Once steady state was reestablished, data taking was recommenced. After satisfactory runs were obtained for the given power level, the input power was reduced to the next point in the series. The desired power levels were 14.0, 12.5, 11.0, 9.5, and 8.0 watts. Some ceramic loadings blanketed the packages and prevented achieving all the desired power levels.

2. Natural Circulation - External Excitation

The runs with external excitation were conducted in the same manner as the unexcited natural circulation runs, with the exception that a small direct current motor was used to vibrate the enclosure. Figure 2-7 is a picture of the motor, eccentric weight and plate used for the external excitation runs.

3. Forced Circulation

The forced circulation data was collected generally in a manner similar to the natural circulation data. Some differences existed. The pump was used to suction drag Fluorinert and fill the system. The small volume of trapped air was vented through the vent line. When ceramic was to be added, the pump suction line was disconnected and the

ceramic was added to the tubing. The pump was then run to distribute the ceramic evenly, prior to energizing the chips. The ceramic addition was limited by the tendency of the ceramic to clog the turbine flowmeter. Following system fill, the monitoring and power supply system were energized and data was collected in the same manner as the natural circulation data, with the same program. Following the collection of a series of data, a separate program was used to measure the flow rate. (see Appendix A)

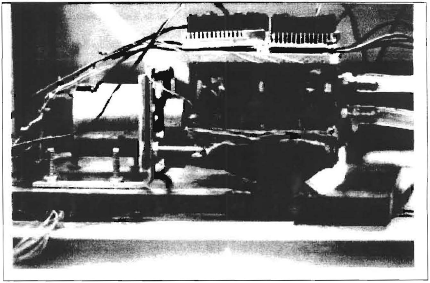

Figure 2-7: Motor, weight and plate used for external excitation runs.

III. EXPERIMENTAL RESULTS

A. DESCRIPTION OF RESULTS

Contained in Appendix B is a complete listing of all the data runs performed for this study. For this investigation, measurements were made of chip temperatures (using diode sensors), ceramic substrate temperatures (using thermocouples), cold plate temperatures (using thermocouples), package voltage drop and precision resistor voltage drop for power input determination. The data has been collated by particle size, type and heating configuration. For each condition, two figures are plotted, (i) total package input power versus the temperature difference between the package diodes and the cold plate, (ii) total package input power and the peak diode temperature. Figures 3-1 through 3-8 show the results of natural circulation for each of the particle types in the horizontal geometry. Figures 3-9 through 3-12 show the results of natural circulation in the vertical geometry. Figures 3-13 and 3-14 show the effect of external excitation for one particle type and size. Figures 3-15 and 3-16 show the effect of forced circulation for one particle type and size.

The figures discussed above are in dimensional form and some difficulty arises when trying to compare the data from different combinations of ceramic and fluid. The results were non-dimensionalized to permit comparison of the data. During the original testing, no temperature data was taken directly on the side of the substrate exposed to the fluid. However, the temperature on the bottom of the substrate was measured by nine

thermocouples as was the external temperature of the case. This permitted estimation of a heat flux through the enclosure case, and then a determination of the substrate fluid interface temperature. Once this surface temperature was estimated, a Rayleigh number was determined. The data collection system provided sufficient data for the determination of a Nusselt number directly. All of the following figures are in non-dimensional form. Figure 3-17 shows the plot of Ra versus Nu for three different loadings of the 3 micron BN particle and a baseline run. Figure 3-18 shows the results of natural circulation for each of the different particle types in the horizontal geometry.

1. Description Of Data - Natural Circulation

As previously discussed, the test surface consisted of a three by three array of leadless chip carrier packages, numbered as shown in Figure 2-3 . Only the center column temperature sensing diodes (labeled 2, 5 and 8 in Figure 2-3) were connected to the data acquisition system. All nine packages were powered in parallel, however, no method was available to determine the variation in power input between the various packages. As shown in Figure 2-4, nine thermocouples, labeled in the same order as the packages in Figure 2-3, mounted to the base of the ceramic substrate were connected to the data acquisition system. These temperatures and the total input power are represented in the following 16 figures.

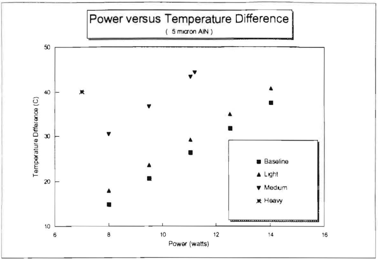

Figure 3-1: Power versus package to plate temperature difference, horizontal geometry.

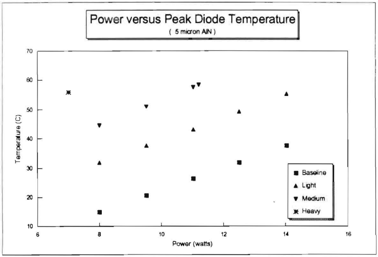

Figure 3-2: Power versus package to peak diode temperature, horizontal geometry.

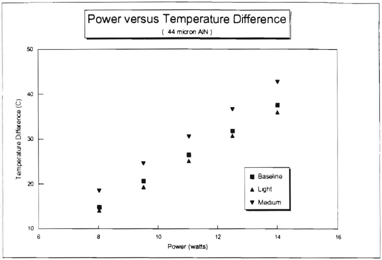

Figure 3-3: Power versus package to plate temperature difference, horizontal geometry.

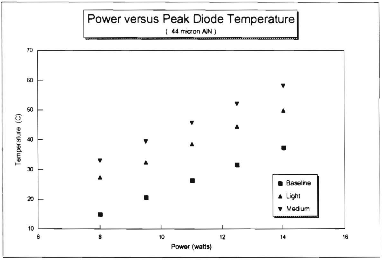

Figure 3-4: Power versus package to peak diode temperature, horizontal geometry.

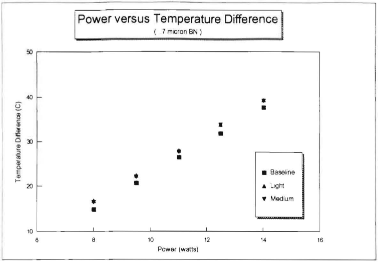

Figure 3-5: Power versus package to plate temperature difference, horizontal geometry.

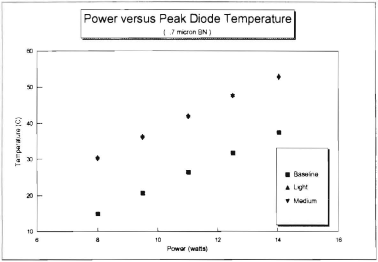

Figure 3-6: Power versus package to peak diode temperature, horizontal geometry.

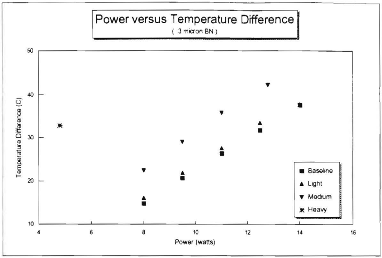

Figure 3-7: Power versus package to plate temperature difference, horizontal geometry.

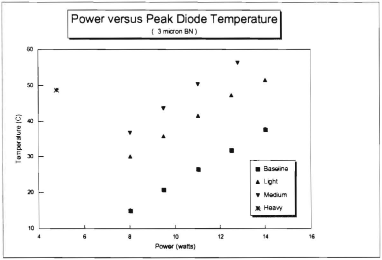

Figure 3-8: Power versus package to peak diode temperature, horizontal geometry.

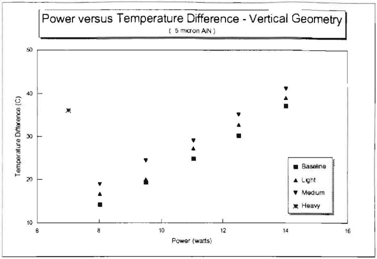

Figure 3-9: Power versus package to plate temperature difference, vertical geometry.

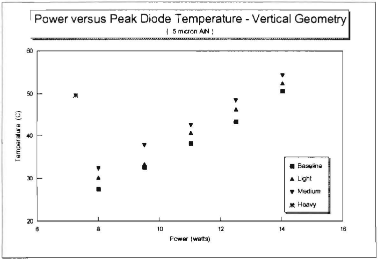

Figure 3-10: Power versus package to peak diode temperature, vertical geometry.

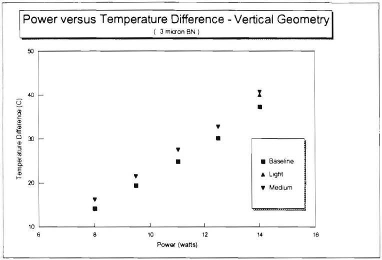

Figure 3-11: Power versus package to plate temperature difference, vertical geometry.

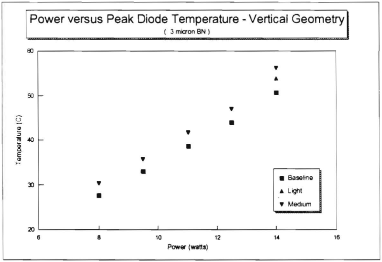

Figure 3-12: Power versus package to peak diode temperature, vertical geometry.

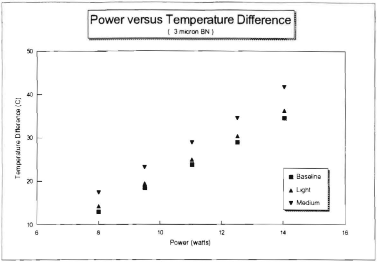

Figure 3-13: Power versus package to plate temperature difference, external excitation.

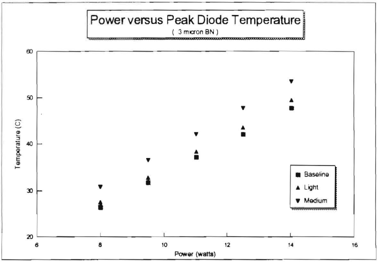

Figure 3-14: Power versus package to peak diode temperature, external excitation.

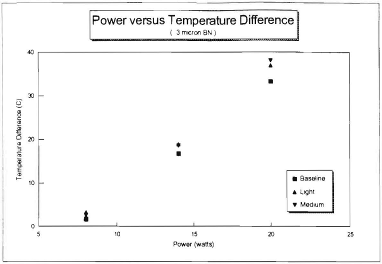

Figure 3-15: Power versus package to plate temperature difference, forced circulation.

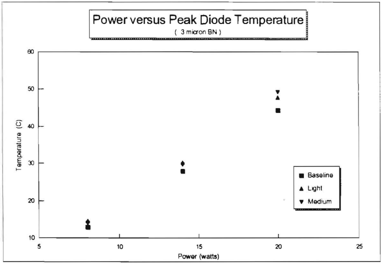

Figure 3-16: Power versus package to peak diode temperature, forced circulation.

B. DISCUSSION OF HORIZONTAL PLATE NATURAL CIRCULATION DATA

A baseline run was conducted using pure FC-75. This baseline was periodically performed throughout the duration of data gathering to verify the data taking system and detect system variations. In the horizontal geometry, two different types of ceramic particles, each having two different sizes were investigated. Boron Nitride was tested in particles of 0.3-0.7 microns, hereinafter referred to as the 0.7 micron BN and 2-3 microns, hereinafter referred to as the 3 micron BN. Aluminum Nitride was tested in particle sizes of 5 microns and 44 microns. Table 3-1 shows the representative loadings that have been called 'light', 'medium' and 'heavy' for ease of reference.

TABLE 3-1: PARTICLE LOADING NOMENCLATURE

Horizontal Geometry

	Light	Medium	Heavy
AlN 44.0 micron	0.1	1.11	NA
AlN 5.0 micron	1.25	10.33	Full
BN 3.0 micron	0.17	0.39	Full
BN 0.7 micron	0.1	0.25	NA

Vertical Geometry

	Light	Medium	Heavy
AlN 5.0 micron	5.07	10.33	Full
BN 3.0 micron	0.17	1.95	Full

External Excitation

	Light	Medium	Heavy
BN 3.0 micron	0.22	1.22	NA

Forced Circulation

	Light	Medium	Heavy
BN 3.0 micron	1.00	3.66	NA

All weights in grams

1. Effect Of Particle Loading

While many of the particle types were tested at various loadings, three general classifications, light, medium and heavy were developed for the loading. Throughout the testing, the heavier loads were seen to diminish the heat transfer capability. Figures 3-1 and 3-2 illustrate the point graphically. As the load is increased to a point where the enclosure is packed as full as possible with AlN, the peak power is reduced. At this point the input power has been reduced to 50% of the desired peak input power, yet the diode temperature has risen by 30°C above the baseline temperature at 14 watts total input power.

2. Effect Of Particle Size

As was discussed earlier, two different particle sizes were tested for each of the two ceramics. Two pairs of figures, Figures 3-1 and 3-3 and Figures 3-5 and 3-7 show the effect of two different particle sizes. The first figure of each pair (Figure 3-1 and 3-5) represents the smaller of the two particles for each material, while the second figure of each pair (Figure 3-3 and 3-7) represents the larger of the two particles for each material. While the loadings are not exactly the same, the larger particles show much more rapid heat transfer decrement as the loading is increased. This was further confirmed by visual observation, as the larger particles were not picked up by the buoyant streams at lower loadings. Figures 3-2, 3-4, 3-6 and 3-8 show the same trend even more prominently in the rapid rise of peak diode temperature for given power levels. The larger particles were so

deleterious that the desired input power was not able to be obtained. For these conditions the input power was limited to avoid exceeding a diode temperature of 135°C.

3. Effect Of Particle Density

Boron Nitride has a density relatively close to that of FC-75 and was observed to be easily lifted off the plate by the plumes that formed above the chips. Aluminum Nitride is quite a bit denser than Boron Nitride and as loading was increased, rapidly blanketed the plate and could not be lifted by the buoyant plumes. Figures 3-1 and Figures 3-5 show that as the Aluminum Nitride load is increased, the ability to transfer heat is reduced faster than the capability is reduced for the Boron Nitride. In fact for the heavy load with Boron Nitride, the peak package temperature is nearly ten degrees cooler than for the Aluminum Nitride case. This is quite unexpected as bulk Aluminum Nitride has a thermal conductivity nearly twice that of Boron Nitride.

C. DISCUSSION OF VERTICAL SUBSTRATE ORIENTATION NATURAL CIRCULATION DATA

A baseline set of data was obtained with the enclosure mounted with the substrate containing the packages in a vertical arrangement. The cold plate was thus also mounted vertically, opposite the packages. This geometry was only tested in a limited number of runs as it was observed that the particles soon fell out of suspension and rested on the bottom wall.

1. Effect Of Particle Loading

The Boron Nitride 3 micron particles and the Aluminum Nitride 5 micron particles were the only types tested across a wide range of particle loads. Figures 3-11 and 3-12 illustrate that the particles had a tendency to fall out of suspension. The temperatures soon came to the same values as the baseline data when there were insufficient particles to rest against the vertical plate. Figures 3-9, 3-10, 3-11 and 3-12 demonstrate that when there were sufficient particles in contact with the plate, reduction in the heat transfer occurred.

2. Effect Of Geometry

Comparison of Figures 3-1 and 3-2 with 3-9 and 3-10, demonstrates that the vertical geometry had a better heat transfer coefficient than the horizontal geometry. This is to be expected, since the horizontal geometry develops cells that interfere with their neighbors. The vertical geometry results in a larger circulation that sweeps the entire wall.

D. DISCUSSION OF EXTERNALLY EXCITED NATURAL CIRCULATION DATA

During the early parts of the study it was noted that as the particle loading increased, the fraction of the particles that were lifted by the buoyant plumes decreased and the packages became covered by particles, decreasing the heat transfer and raising their temperatures. It was also noted earlier that Boron Nitride has a density close to that of the Fluorinert. An external excitation was provided to the enclosure by a small direct current motor to keep the particles suspended in the liquid. As Figures 3-13 and 3-14 illustrate,

there was still a decrement in performance. The decrement was greater than the stationary performance for the same load.

E. DISCUSSION OF FORCED CIRCULATION RESULTS

A baseline run was conducted using pure FC-75. In the forced circulation geometry, only the 3 micron Boron Nitride was investigated. For the forced circulation portion of the study, flowmeter voltage, (converted to flowrate) was also measured. The apparatus failed after testing was completed for one Reynolds number.

As illustrated in Figures 3-15 and 3-16, the addition of particles did not enhance the heat transfer in the forced circulation condition. The different particle loadings exhibited essentially the same performance. The measurements were limited by the ability of the turbine flowmeter to pass the heavier particle loadings and as noted above, the apparatus failed due to mechanical cracking of the ceramic insert at the rear wall early in this testing regime.

F. NONDIMENSIONAL GRAPHS

The data was non-dimensionalized as discussed earlier, with some modifications. Additional thermocouples were installed after the completion of the originally scheduled testing. These were attached to the tops of packages 1, 2, 4 and 5 and were used to obtain an estimate of the fluid-surface interface temperatures. At low loadings, the surface temperature of the packages is within several degrees of the substrate bottom temperature.

At a higher particle loading the difference approaches 10°C at 14 watts total input. The data did not meet the strict repeatability of the previous data due to the cracking noted above and was used to provide an estimate of adjustment of the substrate bottom temperature in conjunction with the technique described earlier.

Only the natural circulation data is presented in non - dimensional form, as the other modes show similar trends. Figure 3-17 represents the data from only the 3 micron Boron Nitride data runs. Figure 3-18 is a representation of the data from representative samples for all the ceramic particles. It is evident that for all particles as the loading is increased the non dimensional Nusselt number decreases for a given Rayleigh number. As the loading increased, the heat transfer capacity of the FC-75 diminished substantially.

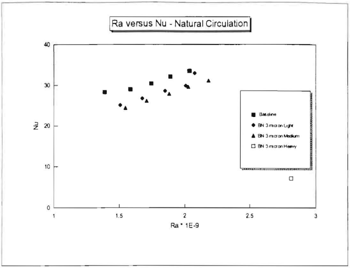

Figure 3-17: Ra versus Nu for 3 micron BN

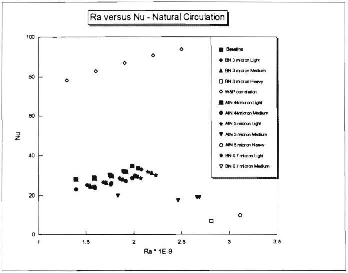

Figure 3-18: Ra versus Nu for natural circulation runs.

IV. NUMERICAL MODEL

A numerical model of the natural convection in the enclosure for a three by three array of packages in the vertical substrate orientation was developed utilizing a control volume approach as described by Patankar [Ref. 20]. The model is similar to that discussed by Wroblewski and Joshi [Ref. 14] for a single package and included the following features: control volumes for velocities that are staggered with respect to those for temperature and pressure; a power law scheme; harmonic mean formulation for the interface diffusivities; the SIMPLER algorithm for the velocity pressure coupling; and a fully implicit forward difference scheme in time. The conjugate conduction in the solid domains was handled numerically by solving the same full set of momentum and energy equations throughout the entire enclosure, but with a large value of viscosity specified for the solid regions.

A. GOVERNING EQUATIONS

The non-dimensional governing equations for the three dimensional unsteady problem, assuming constant properties and the Boussinesq approximation, are as follows:

x momentum;

$$\frac{\partial U}{\partial \tau} + \frac{\partial (UU)}{\partial X} + \frac{\partial (VU)}{\partial Y} + \frac{\partial (WU)}{\partial Z} = -\frac{\partial P}{\partial X} + \left(\frac{Pr}{Ra}\right)^{1/2} * \left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} + \frac{\partial^2 U}{\partial Z^2}\right)$$

y momentum;

$$\frac{\partial V}{\partial \tau} + \frac{\partial (UV)}{\partial X} + \frac{\partial (VV)}{\partial Y} + \frac{\partial (WV)}{\partial Z} = -\frac{\partial P}{\partial Y} + \left(\frac{Pr}{Ra}\right)^{1/2} * \left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} + \frac{\partial^2 V}{\partial Z^2}\right) + \theta$$

z momentum;

$$\frac{\partial W}{\partial \tau} + \frac{\partial (UW)}{\partial X} + \frac{\partial (VW)}{\partial Y} + \frac{\partial (WW)}{\partial Z} = -\frac{\partial P}{\partial Z} + \left(\frac{Pr}{Ra}\right)^{1/2} * \left(\frac{\partial^2 W}{\partial X^2} + \frac{\partial^2 W}{\partial Y^2} + \frac{\partial^2 W}{\partial Z^2}\right)$$

energy (fluid);

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial (U\theta)}{\partial X} + \frac{\partial (V\theta)}{\partial Y} + \frac{\partial (W\theta)}{\partial Z} = \left(\frac{1}{Pr\,Ra}\right)^{1/2} * \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} + \frac{\partial^2 \theta}{\partial Z^2}\right)$$

energy (chip);

$$C_c \frac{\partial \theta}{\partial \tau} = \left(\frac{1}{Pr\,Ra}\right)^{1/2} * \left[R_c\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} + \frac{\partial^2 \theta}{\partial Z^2}\right) + \frac{1}{H_c L_c^2}\right]$$

energy (unheated regions)

$$C_i \frac{\partial \theta}{\partial \tau} = \left(\frac{1}{Pr\,Ra}\right)^{1/2} * \left[R_i\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} + \frac{\partial^2 \theta}{\partial Z^2}\right)\right]$$

The appropriate non-dimensional parameters are $Ra = g\beta Q l^4/A\alpha\nu k_f$, $Pr = \nu/\alpha$, $U = u/U_o$, $V = v/U_o$, $W = w/U_o$, $U_o = (g\beta Q/k_f)^{1/2}$, $\tau = tU_o/l$, $\theta = (T-T_c)/(Q/lk_f)$, $P = p/\rho U_0^2$, $X = x/l$, $Y = x/l$, $Z = z/l$, $H_c = h_c/l$, $L_c = l_c/l$, $R_c = k_c/k_f$, $R_i = k_i/k_f$, $C_c = (\rho c_p)_c/(\rho c_p)_f$ and $C_i = (\rho c_p)_i/(\rho c_p)_f$. The energy equation for unheated regions is applicable to all of the regions within the package except the chip itself. The subscript i refers to these various regions: i = s to the ceramic substrate; i = p to the ceramic package itself, i = l to the lid, i = g to the solder, i = r to the air gap between the chip and the lid, and i = m to the gold and tungsten coating.

The boundary conditions for the enclosure walls are as follows:

$X = 0$; $\partial\theta/\partial X = 0$, $U = 0$, $V = 0$, $W = 0$

$X = X_L$; $\theta = 0$, $U = 0$, $V = 0$, $W = 0$

$Y = 0, X_L$; $\partial\theta/\partial Y = 0$, $U = 0$, $V = 0$, $W = 0$

$Z = 0, X_L$; $\partial\theta/\partial Z = 0$, $U = 0$, $V = 0$, $W = 0$

where $X_L = X/l$.

Figure 4-1 illustrates the axis selection used for the analysis. The substrate is vertically aligned. The axis normal to the package is designated the X - axis, the axis in the vertical plane designated the Y - axis, and the axis parallel to the substrate surface is designated as the Z -axis.

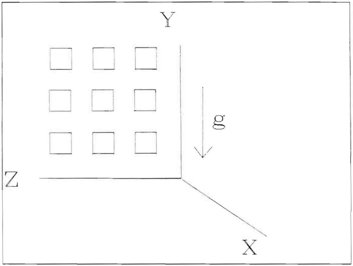

Figure 4-1: Numerical model package orientation and axis selection.

B. SOLUTION TECHNIQUE

The solution was obtained throughout the entire enclosure. The initial nondimensional time step was selected to be $\Delta\tau = 1$ for Ra = 1.15E3. An algorithm within the program expanded the time steps if convergence was reached within a time step in three iterations. Two iterations per time step is the minimum required due to the technique used for convergence checking.

1. Results

a. Base Case

The initial case was similar to the geometry and conditions developed by Wroblewski and Joshi [Ref. 14] for the single chip leadless package. The solver used for that study has been ported from an Amdahl mainframe and refined to run on a Sun Microsystems Sparc10 workstation.

b. Current Case

Once the solver had been verified, the geometry was revised to reflect the three by three array of leadless chip carrier packages that were used for the experimental work. A low Rayleigh number (Ra = 1.15E3) was used to test the stability of the numerical model. For FC-75, this Rayleigh number is equivalent to an input power of only 4.4 microwatts. Thus the problem is primarily conduction heat transfer and the fluid develops very low velocities. Figure 4-2 shows the isotherms for the nine package geometry in the Z - Y plane passing through the plane adjacent to the package lid surfaces, at $\tau = 959$. Figure 4-3 is a plot of the fluid velocities in the same plane as the temperature plot of Figure 4-2. It shows the fluid developing upward velocities in the heated regions. This is still in the transient period discussed by Wroblewski and Joshi. The temperature contours for a vertical cut in the X - Y plane through the center of the middle column of packages are shown in Figure 4-4. The plumes are starting to develop above the packages, but there is very little flow developing in the enclosure. Figure 4-5 shows the velocities in the same plane as Figure 4-4.

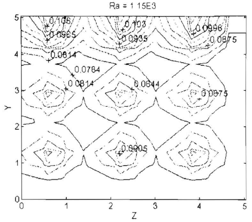

Figure 4-2: Isotherms for Ra = 1.15E3, in the Y - Z plane at X = 0.29. τ = 959.

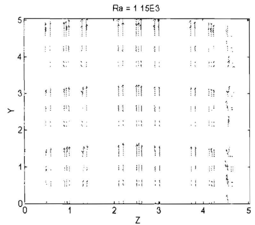

Figure 4-3: ZY velocity vectors for Ra = 1.15E3, in the Y - Z plane at X = 0.29. τ = 959.

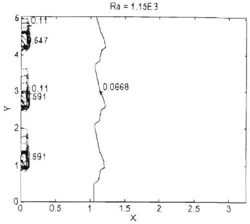

Figure 4-4: Isotherms for Ra = 1.13E7 in the X-Y plane at Z = 2.55. τ = 959.

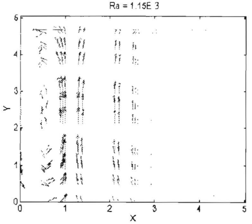

Figure 4-5: XY velocity vectors for Ra = 1.13E7 in the X-Y plane at Z = 2.55. τ = 959.

The model was now reprogrammed for the case of a much higher Rayleigh number. The highest Rayleigh number attained in this study was 1.15E7. This is equivalent to a power input of 44 milliwatts. The following figures are taken at the same positions as the corresponding figures for the case of Ra = 1.15E3. Due to the temperature scaling, the nondimensional temperatures are lower, while the actual temperatures are higher. Figure 4-6 shows the isotherms for the nine package geometry in the Z - Y plane passing through the plane adjacent to the package lid surfaces, at $\tau = 3619$. Figure 4-7 is a plot of the fluid velocities in the same plane as the temperature plot of Figure 4-6. It shows the fluid developing upward velocities in the heated regions. The temperature profiles for a vertical cut in the X - Y plane through the center of the middle column of packages is shown in Figure 4-8. Figure 4-9 shows the velocities in the same plane as Figure 4-8. The plumes are starting to develop above the packages, and the flow velocities are larger in the enclosure. In addition the return flow from the cold plate has begun and flow is beginning to develop the circulation expected for this type of enclosure.

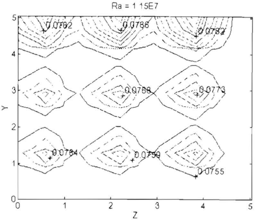

Figure 4-6: Isotherms for Ra = 1.15E7, in the Y - Z plane at X = 0.29. τ = 3516.

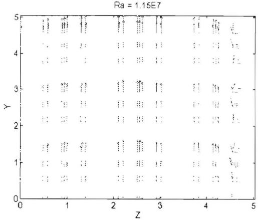

Figure 4-7: ZY velocity vectors for Ra = 1.15E7, in the Y - Z plane at X = 0.29. τ = 3516.

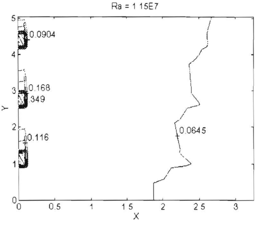

Figure 4-8: Isotherms for Ra = 1.15E7 in the X-Y plane at Z = 2.55. τ = 3516.

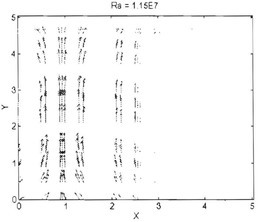

Figure 4-9: XY velocity vectors for Ra = 1.15E7 in the X-Y plane at Z = 2.55. τ = 3516.

V. CONCLUSIONS

The desire to improve the heat transfer performance of Fluorinert-75 through the use of ceramic particles was unsuccessful. The particles and loadings tested all resulted in unchanged or reduced heat transfer capability than the pure FC-75. The larger particles caused a greater decrement than the smaller particles due to their increased propensity to resist the buoyant streams and rest on the face of the chips. The .3 micron Boron Nitride, which was the smallest particle and has the density closest to the Fluorinert, caused the smallest decrement in heat transfer.

The external excitation proved to be successful in suspending the particles from the plate, but still resulted in a heat transfer decrement.

The forced circulation data showed the relative insensitivity of the heat transfer capability of the Fluorinert to the addition of particles in this regime. It also demonstrated the dangers of using forced circulation in direct electronic cooling. Throughout the natural convection testing, extending over a period of greater than six months, no damage had been encountered to the packages. In the forced circulation testing the packages failed in four days, most probably due to flow induced vibration of the divider plate. The danger in actual electronic equipment of similar phenomena should be a key consideration in the design of direct immersion cooling schemes. The results of this testing indicate that for the

materials tested, and possibly for a wider range of ceramic materials, the particles do not enhance the heat transfer characteristics.

The three dimensional numerical model was successfully modified to model the geometry encountered in this study for the vertical substrate orientation. The model was able to adequately represent the expected temperature profiles.

VI. RECOMMENDATIONS

The following recommendation are made for further study:

1. Investigate the physical reason for the failure of high thermal conductivity particles to raise the overall mixture thermal conductivity.
2. Investigate particles that more closely match the density of the Fluorinert.
3. Refine the mesh used for the numerical model to concentrate in the regions with large gradients.

APPENDIX A

POWER AND TEMPERATURE ACQUISITION PROGRAMS

A. DATA MONITORING PROGRAM

```
100!!!!!!!!!!!!!!!!!!!!!
110!! DATA COLLECTION
120!! MONITORING FOR EQUILIBRIUM
130 !! V(0) MONITORS VOLTAGE DROP ACROSS
140 !! THE PRECISION RESISTOR
150 !! V(1) MONITORS THE VOLTAGE DROP ACROSS THE
160 !! CHIP SET
170 !! O() MONITORS THE DIODE OHMS
180 !! T() ARE THE TEMPERATURES
190 !! T(0) IS THE AMBIENT
200 !! T(1-9) ARE THE CHIPS
210 !! T(10) IS NOT USED
220 !! T(11-14) ARE THE UNDER PLATE
240 !! T(16-17) ARE THE SIDE WALLS
250  REAL V(1),O(2),T(17)
260  REAL Vt(1,10),Ot(2,10),Tt(17,10)
261  PRINT "PWR"
263  INPUT Pwr
270  PRINTER IS CRT
280  CLEAR SCREEN
290  J=0
300  OUTPUT 709;"RST"
310  OUTPUT 709;"REAL V(1),O(2),T(16)"
320  OUTPUT 709;"CONFMEAS DCV,203-204,USE 700"
330  ENTER 709;V(*)
340  PRINT V(0),V(1),V(0)*V(1)/.101
350  Vt(0,J)=V(0)
360  Vt(1,J)=V(1)
370  Vt(0,10)=Vt(0,10)+V(0)
380  Vt(1,10)=Vt(1,10)+V(1)
390  OUTPUT 709;"CONFMEAS OHM,200-202,USE 700"
400  ENTER 709;O(*)
410  Ot(0,J)=(7234.555-O(0))/19.9904
420  Ot(1,J)=(7241.029-O(1))/20.0697
430  Ot(2,J)=(7241.567-O(2))/20.0871
440  PRINT Ot(0,J)
450  PRINT Ot(1,J)
460  PRINT Ot(2,J)
470  Ot(0,10)=Ot(0,10)+Ot(0,J)
480  Ot(1,10)=Ot(1,10)+Ot(1,J)
490  Ot(2,10)=Ot(2,10)+Ot(2,J)
```

```
500  OUTPUT 709;"CONFMEAS TEMPT,300-309,311-316,318,USE 700,INTO T"
510  OUTPUT 709;"VREAD T"
520  FOR I=0 TO 16
530    ENTER 709;T(I)
540    IF I<10 OR I>14 THEN 560
550    IF T(I)>60 THEN BEEP
560    PRINT I,T(I)
570    Tt(I,J)=T(I)
580    Tt(I,10)=Tt(I,10)+T(I)
590  NEXT I
600  Tave=0
610  FOR I=10 TO 13
620    Tave=Tave+T(I)
630  NEXT I
640  PRINT Tave/4
650  J=J+1
660  IF J=10 THEN 680
670  GOTO 320
680  PRINT Vt(0,10)/J
690  PRINT Vt(1,10)/J
691  Power=Vt(0,10)*Vt(1,10)/(.101*J*J)
700  PRINT Power
710  Vt(0,10)=0
720  Vt(1,10)=0
730  PRINT Ot(0,10)/J
740  PRINT Ot(1,10)/J
750  PRINT Ot(2,10)/J
760  Ot(0,10)=0
770  Ot(1,10)=0
780  Ot(2,10)=0
790  FOR I=0 TO 16
800    PRINT I,Tt(I,J)/10
810    Tt(I,J)=0
820  NEXT I
830  PRINT "Tave =";Tave/4
840  PRINT
841  IF Tave<23.8*4 OR Tave>24.2*4 THEN 850
842  IF ABS(Power-Pwr)>.05 THEN 850
843  BEEP
844  PRINT "STEADY STATE MET"
850  K=K+1
860  PRINT K
870  PRINT
```

```
880  GOTO 290
890  END
```

B. DATA ACQUISITION PROGRAM

```
100!!!!!!!!!!!!!!!!!!!!!!
110!! DATA COLLECTION FILE
120!! ENTER THE RUN TYPE
150 !! V(0) MONITORS VOLTAGE DROP ACROSS
160 !! THE PRECISION RESISTOR
170 !! V(1) MONITORS THE VOLTAGE DROP ACROSS THE
180 !! PACKAGES
190 !! O() MONITORS THE DIODE OHMS
200 !! T() ARE THE TEMPERATURES
210 !! T(0) IS THE AMBIENT
220 !! T(1-9) ARE THE CHIPS
230 !! T(10) IS NOT USED
240 !! T(11-14) ARE THE UNDER PLATE
250 !! T(15) IS THE PELTIER
260 !! T(16-17) ARE THE SIDE WALLS
270  REAL V(1),O(2),T(17),Ts
280  REAL Vt(1,10),Ot(2,10),Tt(17,10)
290  PRINTER IS CRT
300  CLEAR SCREEN
310  PRINT "INPUT TARGET POWER LEVEL: "
320  INPUT Pwr
330  Geom$="H - FC"
340  PRINTER IS 9
350  Fluid$="FC 75"
360  Ceramic$="3m BN"
370  Grams=3.66
380  PRINT "THIS RUN IS AT ";Pwr;" WATTS"
390  PRINT DATE$(TIMEDATE),TIME$(TIMEDATE)
400  PRINT "THE FLUID IS: ";Fluid$;", ARRANGEMENT IS: ";Geom$
410  PRINT "THE CERAMIC IS: ";Ceramic$
420  PRINT "THE CERAMIC WEIGHT IS: ";Grams;" GRAMS"
430  J=0
440  OUTPUT 709;"RST"
450  OUTPUT 709;"REAL V(1),O(2),T(16)"
```

```
460  OUTPUT 709;"CONFMEAS DCV,203-204,USE 700"
470  ENTER 709;V(*)
480  PRINT V(0)
490  PRINT V(1)
500  PRINT V(0)*V(1)/.101
510  OUTPUT 709;"CONFMEAS OHM,200-202,USE 700"
520  ENTER 709;O(*)
530  PRINT (7234.555-O(0))/19.9904
540  PRINT (7241.029-O(1))/20.0697
550  PRINT (7241.567-O(2))/20.0871
560  OUTPUT 709;"CONFMEAS TEMPT,300-309,311-316,318,USE 700,INTO T"
570  OUTPUT 709;"VREAD T"
580  FOR I=0 TO 16
590   ENTER 709;T(I)
600   IF I<10 THEN 640
610   IF T(I)>60 THEN BEEP
620   IF I>13 THEN 640
630   Ts=Ts+T(I)
640   PRINT T(I)
650  NEXT I
660  J=J+1
670  IF J=10 THEN 690
680  GOTO 460
690  PRINT DATE$(TIMEDATE),TIME$(TIMEDATE)
700  PRINT "DATA RUN ENDED "
710  PRINTER IS CRT
720  PRINT Ts/40
730  END
```

C. FLOWRATE COLLECTION PROGRAM

```
100!!!!!!!!!!!!!!!!!!!!!
110!! FLOW METER CALIBRATION
120 !! F(0) MONITORS THE VOLTAGE ACROSS THE
130 !! FLOWMETER
140  REAL F(0)
150  REAL Ft(10)
160  PRINTER IS CRT
170  CLEAR SCREEN
180  PRINT "RHEOSTAT SETTING"
190  INPUT R
```

```
200 J=0
210 OUTPUT 709;"RST"
220 OUTPUT 709;"REAL F(0)"
230 OUTPUT 709;"CONFMEAS DCV,205,USE 700"
240 ENTER 709;F(*)
250 F(0)=F(0)*(-1.0)
260 PRINT "FLOW  ";F(0)
270 Ft(J)=F(0)
280 FOR N=1 TO 2000
290 NEXT N
300 J=J+1
310 IF J=10 THEN 330
320 GOTO 210
330 PRINT "ELAPSED TIME"
340 INPUT Ti
350 PRINT "ML PUMPED"
360 INPUT Ml
370 PRINTER IS 9
380 PRINT "CALIBRATION"
390 PRINT "DIAL SETTING  ",R
400 FOR J=1 TO 10
410 PRINT Ft(J)
420 NEXT J
430 PRINT "ELAPSED TIME ";Ti
440 PRINT "VOLUME (ML) ";Ml
450 PRINTER IS CRT
460 END
```

APPENDIX B

LIST OF RUNS

Run Name	Ceramic	Size Microns	Load Grams	Power Watts	Orientation
C0_14	None	NA	NA	14	Horizontal
C0_12.5	None	NA	NA	12.5	Horizontal
C0_11	None	NA	NA	11	Horizontal
C0_9.5	None	NA	NA	9.5	Horizontal
C0_8	None	NA	NA	8	Horizontal
A1_14	AIN	5	1.25	14	Horizontal
A1_125	AIN	5	1.25	12.5	Horizontal
A1_11	AIN	5	1.25	11	Horizontal
A1_9.5	AIN	5	1.25	9.5	Horizontal
A1_8	AIN	5	1.25	8	Horizontal
A2_14	AIN	5	2.52	14	Horizontal
A2_125	AIN	5	2.52	12.5	Horizontal
A2_11	AIN	5	2.52	11	Horizontal
A2_9.5	AIN	5	2.52	9.5	Horizontal
A2_8	AIN	5	2.52	8	Horizontal
A3_115	AIN	5	5.07	11.5	Horizontal
A3_11	AIN	5	5.07	11	Horizontal
A3_9.5	AIN	5	5.07	9.5	Horizontal
A3_8	AIN	5	5.07	8	Horizontal
A4_113	AIN	5	10.33	11.3	Horizontal
A4_11	AIN	5	10.33	11	Horizontal
A4_9.5	AIN	5	10.33	9.5	Horizontal
A4_8	AIN	5	10.33	8	Horizontal
A5_7	AIN	5	full	8	Horizontal
B1_14	BN	3	1.95	14	Horizontal
B1_125	BN	3	1.95	12.5	Horizontal
B1_11	BN	3	1.95	11	Horizontal
B1_9.5	BN	3	1.95	9.5	Horizontal
B1_8	BN	3	1.95	8	Horizontal

Run Name	Ceramic	Size Microns	Load Grams	Power Watts	Orientation
B2_14	BN	3	.166	14	Horizontal
B2_125	BN	3	.166	12.5	Horizontal
B2_11	BN	3	.166	11	Horizontal
B2_9.5	BN	3	.166	9.5	Horizontal
B2_8	BN	3	.166	8	Horizontal
B3_14	BN	3	0.303	14	Horizontal
B3_125	BN	3	0.303	12.5	Horizontal
B3_11	BN	3	0.303	11	Horizontal
B3_9.5	BN	3	0.303	9.5	Horizontal
B3_8	BN	3	0.303	8	Horizontal
B4_14	BN	3	0.393	14	Horizontal
B4_125	BN	3	0.393	12.5	Horizontal
B4_11	BN	3	0.393	11	Horizontal
B4_9.5	BN	3	0.393	9.5	Horizontal
B4_8	BN	3	0.393	8	Horizontal
B5_14	BN	3	0.016	14	Horizontal
B5_125	BN	3	0.016	12.5	Horizontal
B5_11	BN	3	0.016	11	Horizontal
B5_9.5	BN	3	0.016	9.5	Horizontal
B5_8	BN	3	0.016	8	Horizontal
B6_14	BN	3	0.054	14	Horizontal
B6_125	BN	3	0.054	12.5	Horizontal
B6_11	BN	3	0.054	11	Horizontal
B6_9.5	BN	3	0.054	9.5	Horizontal
B6_8	BN	3	0.054	8	Horizontal
B7_14	BN	3	0.097	14	Horizontal
B7_125	BN	3	0.097	12.5	Horizontal
B7_11	BN	3	0.097	11	Horizontal
B7_9.5	BN	3	0.097	9.5	Horizontal
B7_8	BN	3	0.097	8	Horizontal

Run Name	Ceramic	Size Microns	Load Grams	Power Watts	Orientation
B8_14	BN	3	0.115	14	Horizontal
B8_125	BN	3	0.115	12.5	Horizontal
B8_11	BN	3	0.115	11	Horizontal
B8_9.5	BN	3	0.115	9.5	Horizontal
B8_8	BN	3	0.115	8	Horizontal
B9_14	BN	3	0.164	14	Horizontal
B9_125	BN	3	0.164	12.5	Horizontal
B9_11	BN	3	0.164	11	Horizontal
B9_9.5	BN	3	0.164	9.5	Horizontal
B9_8	BN	3	0.164	8	Horizontal
D1_14	BN	3	0.05	14	Horizontal
D1_125	BN	3	0.05	12.5	Horizontal
D1_11	BN	3	0.05	11	Horizontal
D1_9.5	BN	3	0.05	9.5	Horizontal
D1_8	BN	3	0.05	8	Horizontal
D2_14	BN	3	0.099	14	Horizontal
D2_125	BN	3	0.099	12.5	Horizontal
D2_11	BN	3	0.099	11	Horizontal
D2_9.5	BN	3	0.099	9.5	Horizontal
D2_8	BN	3	0.099	8	Horizontal
D3_14	BN	3	0.155	14	Horizontal
D3_125	BN	3	0.155	12.5	Horizontal
D3_11	BN	3	0.155	11	Horizontal
D3_9.5	BN	3	0.155	9.5	Horizontal
D3_8	BN	3	0.155	8	Horizontal
D4_5	BN	3	full	4.8	Horizontal
E1_14	BN	0.7	0.051	14	Horizontal
E1_125	BN	0.7	0.051	12.5	Horizontal
E1_11	BN	0.7	0.051	11	Horizontal
E1_9.5	BN	0.7	0.051	9.5	Horizontal
E1_8	BN	0.7	0.051	8	Horizontal

Run Name	Ceramic	Size Microns	Load Grams	Power Watts	Orientation
E2_14	BN	0.7	0.100	14	Horizontal
E2_125	BN	0.7	0.100	12.5	Horizontal
E2_11	BN	0.7	0.100	11	Horizontal
E2_9.5	BN	0.7	0.100	9.5	Horizontal
E2_8	BN	0.7	0.100	8	Horizontal
E3_14	BN	0.7	0.150	14	Horizontal
E3_125	BN	0.7	0.150	12.5	Horizontal
E3_11	BN	0.7	0.150	11	Horizontal
E3_9.5	BN	0.7	0.150	9.5	Horizontal
E3_8	BN	0.7	0.150	8	Horizontal
E4_14	BN	0.7	0.248	14	Horizontal
E4_125	BN	0.7	0.248	12.5	Horizontal
E4_11	BN	0.7	0.248	11	Horizontal
E4_9.5	BN	0.7	0.248	9.5	Horizontal
E4_8	BN	0.7	0.248	8	Horizontal
F1_14	AlN	44	0.049	14	Horizontal
F1_125	AlN	44	0.049	12.5	Horizontal
F1_11	AlN	44	0.049	11	Horizontal
F1_9.5	AlN	44	0.049	9.5	Horizontal
F1_8	AlN	44	0.049	8	Horizontal
F2_14	AlN	44	0.103	14	Horizontal
F2_125	AlN	44	0.103	12.5	Horizontal
F2_11	AlN	44	0.103	11	Horizontal
F2_9.5	AlN	44	0.103	9.5	Horizontal
F2_8	AlN	44	0.103	8	Horizontal
F3_14	AlN	44	0.207	14	Horizontal
F3_125	AlN	44	0.207	12.5	Horizontal
F3_11	AlN	44	0.207	11	Horizontal
F3_9.5	AlN	44	0.207	9.5	Horizontal
F3_8	AlN	44	0.207	8	Horizontal

Run Name	Ceramic	Size Microns	Load Grams	Power Watts	Orientation
F4_14	AlN	44	1.11	14	Horizontal
F4_125	AlN	44	1.11	12.5	Horizontal
F4_11	AlN	44	1.11	11	Horizontal
F4_9.5	AlN	44	1.11	9.5	Horizontal
F4_8	AlN	44	1.11	8	Horizontal
V0_14	None	NA	NA	14	Vertical
V0_125	None	NA	NA	12.5	Vertical
V0_11	None	NA	NA	11	Vertical
V0_9.5	None	NA	NA	9.5	Vertical
V0_8	None	NA	NA	8	Vertical
V3A_14	AlN	44	5.07	14	Vertical
V3A_125	AlN	44	5.07	12.5	Vertical
V3A_11	AlN	44	5.07	11	Vertical
V3A_9.5	AlN	44	5.07	9.5	Vertical
V3A_8	AlN	44	5.07	8	Vertical
V4A_14	AlN	44	10.33	14	Vertical
V4A_125	AlN	44	10.33	12.5	Vertical
V4A_11	AlN	44	10.33	11	Vertical
V4A_9.5	AlN	44	10.33	9.5	Vertical
V4A_8	AlN	44	10.33	8	Vertical
V5A_8	AlN	44	full	8	Vertical
V1B_14	BN	3	1.95	14	Vertical
V1B_125	BN	3	1.95	12.5	Vertical
V1B_11	BN	3	1.95	11	Vertical
V1B_9.5	BN	3	1.95	9.5	Vertical
V1B_8	BN	3	1.95	8	Vertical
V2B_14	BN	3	.166	14	Vertical
V2B_125	BN	3	.166	12.5	Vertical
V2B_11	BN	3	.166	11	Vertical
V2B_9.5	BN	3	.166	9.5	Vertical
V2B_8	BN	3	.166	8	Vertical

Run Name	Ceramic	Size Microns	Load Grams	Power Watts	Orientation
E1B_14	None	NA	NA	14	Excitation
E1B_125	None	NA	NA	12.5	Excitation
E1B_11	None	NA	NA	11	Excitation
E1B_9.5	None	NA	NA	9.5	Excitation
E1B_8	None	NA	NA	8	Excitation
E2B_14	BN	3	0.22	14	Excitation
E2B_125	BN	3	0.22	12.5	Excitation
E2B_11	BN	3	0.22	11	Excitation
E2B_9.5	BN	3	0.22	9.5	Excitation
E2B_8	BN	3	0.22	8	Excitation
E3B_14	BN	3	1.22	14	Excitation
E3B_125	BN	3	1.22	12.5	Excitation
E3B_11	BN	3	1.22	11	Excitation
E3B_9.5	BN	3	1.22	9.5	Excitation
E3B_8	BN	3	1.22	8	Excitation
FC1B_20	None	NA	NA	20	Forced
FC1B_14	None	NA	NA	14	Forced
FC1B_8	None	NA	NA	8	Forced
FC2B_20	BN	3	1.0	20	Forced
FC2B_14	BN	3	1.0	14	Forced
FC2B_8	BN	3	1.0	8	Forced
FC3B_20	BN	3	3.66	20	Forced
FC3B_14	BN	3	3.66	14	Forced
FC3B_8	BN	3	3.66	8	Forced

APPENDIX C

SAMPLE UNCERTAINTY CALCULATIONS

The accuracy of the data in this study was determined by performing an uncertainty analysis. For a function comprising a number of independent measurements, $F=F(X_A, X_B, X_C)$, the uncertainty of F was calculated as:

$$\delta F = [(\frac{\partial F}{\partial X_A}\delta X_A)^2 + (\frac{\partial F}{\partial X_B}\delta X_B)^2 + (\frac{\partial F}{\partial X_C}\delta X_C)^2]^{1/2}$$

If the function $F= K*X^a_A*X^b_B*X^c_C$, then the uncertainty was determined by:

$$\frac{\delta F}{F} = [(a\frac{\delta X_A}{X_A})^2 + (b\frac{\delta X_B}{X_B})^2 + (c\frac{\delta X_C}{X_C})^2]^{1/2}$$

The properties of concern:

$T_{plate}= 23.9°C$	$\delta T_{plate}= 0.25°C$
$T_{surf} = 69.5°C$	$\delta T_{surf}= 0.25°C$
$Q = 14.0$ watts	$\delta Q = 0.25$ watts
$\rho = 1654\ kg/m^3$	$\delta\rho = 4.54\ kg/m^3$
$\beta= 0.00148\ K^{-1}$	$\delta\beta= 3.46E\text{-}6K^{-1}$
$c_p=1004$ joule/kgK	$\delta c_p=2.4$ joule/kgK
$\nu=4.603E\text{-}7m^2/s$	$\delta\nu=1.64E\text{-}8m^2/s$
$\alpha=3.585E\text{-}8m^2/s$	$\delta\alpha=1.26E\text{-}10m^2/s$
$k=0.058W/m*K$	$\delta k=4.30E\text{-}5\ W/m*K$
$L=0.009$ m	$\delta L= 0.00009$ m
$A= 0.001137\ m^2$	$\delta A=1.0E\text{-}4\ m^2$
$g=9.807\ m/s^2$	

Uncertainty calculations are for the 3 micron BN light load at maximum power, that is mean power input of 14 watts.

$$\Delta T = T_s - T_{plate}$$

$$Nu = \frac{Q \bullet L}{k \bullet A \bullet (\Delta T)}$$

$$Nu = 33.89$$

With the properties listed above δNu =2.36 or 6.97 %. The Rayleigh Number (Ra) is dependent on β, c_p, k, ν, ρ and α, all of which vary with temperature for FC-75 [Ref. 21]

$$\frac{\delta Nu}{Nu} = [(\frac{\delta Q}{Q})^2 + (\frac{\delta L}{L})^2 + (\frac{\delta A}{A})^2 + (\frac{\delta(\Delta T)}{\Delta T})^2]^{1/2}$$

$$\beta = \frac{0.00246}{1.825 - 0.00246 * T}$$

$$c_p = (0.2411 + 3.7037E - 4 * T)$$

$$k = 0.065 - 7.895E - 5 * T$$

$$\upsilon = [1.4074 - 1.96E - 2 * T + 3.8018E - 4 * T^2 - 2.731E - 6 * T^3 + 8.168E - 9 * T^4] * 10^{-6}$$

$$\rho = (1.825 - 0.00246 * T) * 100$$

$$\alpha = \frac{k}{\rho * c_p}$$

Thus

$$\frac{\delta Ra}{Ra} = [(\frac{\delta Q}{Q})^2 + (4\frac{\delta L}{L})^2 + (\frac{\delta A}{A})^2 + (\frac{\delta \beta}{\beta})^2 + (\frac{\delta k}{k})^2 + (\frac{\delta \alpha}{\alpha})^2 + (\frac{\delta \nu}{\nu})^2]^{1/2}$$

where $Ra = \frac{g\beta QL^4}{k\alpha\nu A}$; Ra = 9.93E8 and δRa = 8.61E7 or 8.67%.

APPENDIX D

NUMERICAL ANALYSIS PROGRAM

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C    A GENERAL PURPOSE FORTRAN PROGRAM FOR SOLVING THREE-   $
C    DIMENSIONAL HEAT TRANSFER AND FLUID FLOW IN RECTANGULAR $
C    COORDINATES                              $
C
C     VERSION OF PROGRAM WHICH CAN USE LARGE ARRAYS FOR
C     FINER GRIDS AND DO USTEADY CALCULATIONS
C     CALCULATIONS FOR LARGE ARRAY VERSION ARE THE SAME AS THOSE
C     FOR THE LOWER DIMENSION PROGRAM EXCPET THAT
C     COEFFICIENTS FOR F.D. EQUATIONS ARE RECLALCULATED
C     RATHER THAN STORED AND REUSED LATER
C     THIS REQUIRES APPROXIMATELY 25 PERCENT MORE TIME FOR EXECUTION
C
cC    DEVELOPED BY:
C    S. B. SATHE
C    CODE 69ST, DEPARTMENT OF MECHANICAL ENGINEERING
C    U.S. NAVAL POSTGRADUATE SCHOOL
C    MONTEREY, CA 93943
C    TEL: (408)-646-2417
C    BITNET ADDRESS: 5140P@NAVPGS
C
C    MODIFIED FOR UNSTEADY OPERATION BY:
C    D. E. WROBLEWSKI
C    CODE 69WRO, DEPARTMENT OF MECHANICAL ENGINEERING
C    U.S. NAVAL POSTGRADUATE SCHOOL
C    MONTEREY, CA 93943
C    TEL: (408)-646-2465
 Relaxation =0.4
c DT=1.
C Tnought=0.75
C EPST=.05
c RA=1.15e3
C uses multiply logic for convergence
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C***********************************************************
c     LOGICAL LSTOP
c     INTEGER*4 NOW(14)
c     COMMON/CNTL/LSTOP,ICALL,ISTOP
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
```

```
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/RESID/RMAX(13),IRESID
      COMMON/SORC/SMAX,SSUM
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1       (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2       ,(F(1,1,1,5),T(1,1,1))
C************************************************************
open(16,file='pcoord')
open(20,file='prhos')
      ISTOP=0
      CALL MESH
      CALL GEOMET
      CALL BEGIN
   10 CALL VARRHO
19999 FORMAT(' LSTOP= ',I2)
      CALL BNDRY
      CALL PRTOUT
      CALL INCRV
      IF(LSTOP) THEN
WRITE(*,19999) ISTOP
STOP
      ENDIF
      CALL COEFF
      GO TO 10
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE PROFIL
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      COMMON/COEF/FLOW,DIFF,ACOF
C************************************************************
      ACOF=DIFF
cprint*,ACOF,DIFF
c     flow=0.
      IF(FLOW.EQ.0.) RETURN
      TEMP=DIFF-ABS(FLOW)*0.1
```

```
      ACOF=0.
      IF(TEMP.LE.0.) RETURN
      TEMP=TEMP/DIFF
      ACOF=DIFF*TEMP**5
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE TDMA
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
       COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      DIMENSION D(35),VAR(35),VARM(35),VARP(35),PHIBAR(35)
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
C***********************************************************
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      COMMON/COEF/FLOW,DIFF,ACOF
      ISTF=IST-1
      JSTF=JST-1
      KSTF=KST-1
      IT1=L2+IST
      IT2=L3+IST
      JT1=M2+JST
      JT2=M3+JST
      KT1=N2+KST
      KT2=N3+KST
C----------------------------------------
      NTSSS=NTIMES(NF)
cprint*,NF,NTSSS
      DO 999 NT=1,NTSSS
      DO 391 N=NF,NF
```

```
C
   IF(.NOT.LBLK(NF))GO TO 60
  60 CONTINUE
COMMENCE TDMA LINE BY LINE SWEEPS FOR SOLUTION
   DO 90 K=KST,N2
   DO 90 J=JST,M2
   PT(ISTF)=0.
   QT(ISTF)=F(ISTF,J,K,N)
   DO 70 I=IST,L2
   DENOM=AP(I,J,K)-PT(I-1)*AIM(I,J,K)
   PT(I)=AIP(I,J,K)/DENOM
   TEMP=CON(I,J,K)+AJP(I,J,K)*F(I,J+1,K,N)+AJM(I,J,K)*F(I,J-1,K,N)
   1         +AKP(I,J,K)*F(I,J,K+1,N)+AKM(I,J,K)*F(I,J,K-1,N)
   QT(I)=(TEMP+AIM(I,J,K)*QT(I-1))/DENOM

  70 CONTINUE
   DO 80 II=IST,L2
   I=IT1-II
  80 F(I,J,K,N)=F(I+1,J,K,N)*PT(I)+QT(I)
  90 CONTINUE
C-----------------------------------
   DO 190 KK=KST,N3
   K=KT2-KK
   DO 190 JJ=JST,M3
   J=JT2-JJ
   PT(ISTF)=0.
   QT(ISTF)=F(ISTF,J,K,N)
   DO 170 I=IST,L2
   DENOM=AP(I,J,K)-PT(I-1)*AIM(I,J,K)
   PT(I)=AIP(I,J,K)/DENOM
   TEMP=CON(I,J,K)+AJP(I,J,K)*F(I,J+1,K,N)+AJM(I,J,K)*F(I,J-1,K,N)
   1         +AKP(I,J,K)*F(I,J,K+1,N)+AKM(I,J,K)*F(I,J,K-1,N)
   QT(I)=(TEMP+AIM(I,J,K)*QT(I-1))/DENOM
  170 CONTINUE
   DO 180 II=IST,L2
   I=IT1-II
  180 F(I,J,K,N)=F(I+1,J,K,N)*PT(I)+QT(I)
  190 CONTINUE
C-----------------------------------
   DO 290 I=IST,L2
   DO 290 K=KST,N2
   PT(JSTF)=0.
   QT(JSTF)=F(I,JSTF,K,N)
   DO 270 J=JST,M2
   DENOM=AP(I,J,K)-PT(J-1)*AJM(I,J,K)
   PT(J)=AJP(I,J,K)/DENOM
   TEMP=CON(I,J,K)+AKP(I,J,K)*F(I,J,K+1,N)+AKM(I,J,K)*F(I,J,K-1,N)
   1         +AIP(I,J,K)*F(I+1,J,K,N)+AIM(I,J,K)*F(I-1,J,K,N)
   QT(J)=(TEMP+AJM(I,J,K)*QT(J-1))/DENOM
  270 CONTINUE
   DO 280 JJ=JST,M2
```

```
      J=JT1-JJ
  280 F(I,J,K,N)=F(I,J+1,K,N)*PT(J)+QT(J)
  290 CONTINUE
C--------------------------------------------
      DO 390 II=IST,L3
      I=IT2-II
      DO 390 KK=KST,N3
      K=KT2-KK
      PT(JSTF)=0.
      QT(JSTF)=F(I,JSTF,K,N)
      DO 370 J=JST,M2
      DENOM=AP(I,J,K)-PT(J-1)*AJM(I,J,K)
      PT(J)=AJP(I,J,K)/DENOM
      TEMP=CON(I,J,K)+AKP(I,J,K)*F(I,J,K+1,N)+AKM(I,J,K)*F(I,J,K-1,N)
     1        +AIP(I,J,K)*F(I+1,J,K,N)+AIM(I,J,K)*F(I-1,J,K,N)
      QT(J)=(TEMP+AJM(I,J,K)*QT(J-1))/DENOM
  370 CONTINUE
      DO 380 JJ=JST,M2
      J=JT1-JJ
  380 F(I,J,K,N)=F(I,J+1,K,N)*PT(J)+QT(J)
  390 CONTINUE
C--------------------------------------------
      DO 490 J=JST,M2
      DO 490 I=IST,L2
      PT(KSTF)=0.
      QT(KSTF)=F(I,J,KSTF,N)
      DO 470 K=KST,N2
      DENOM=AP(I,J,K)-PT(K-1)*AKM(I,J,K)
      PT(K)=AKP(I,J,K)/DENOM
      TEMP=CON(I,J,K)+AIP(I,J,K)*F(I+1,J,K,N)+AIM(I,J,K)*F(I-1,J,K,N)
     1        +AJP(I,J,K)*F(I,J+1,K,N)+AJM(I,J,K)*F(I,J-1,K,N)
      QT(K)=(TEMP+AKM(I,J,K)*QT(K-1))/DENOM
  470 CONTINUE
      DO 480 KK=KST,N2
      K=KT1-KK
  480 F(I,J,K,N)=F(I,J,K+1,N)*PT(K)+QT(K)
  490 CONTINUE
C--------------------------------------------
      DO 590 JJ=JST,M3
      J=JT2-JJ
      DO 590 II=IST,L3
      I=IT2-II
      PT(KSTF)=0.
      QT(KSTF)=F(I,J,KSTF,N)
      DO 570 K=KST,N2
      DENOM=AP(I,J,K)-PT(K-1)*AKM(I,J,K)
      PT(K)=AKP(I,J,K)/DENOM
      TEMP=CON(I,J,K)+AIP(I,J,K)*F(I+1,J,K,N)+AIM(I,J,K)*F(I-1,J,K,N)
     1        +AJP(I,J,K)*F(I,J+1,K,N)+AJM(I,J,K)*F(I,J-1,K,N)
      QT(K)=(TEMP+AKM(I,J,K)*QT(K-1))/DENOM
  570 CONTINUE
```

```
      DO 580 KK=KST,N2
      K=KT1-KK
  580 F(I,J,K,N)=F(I,J,K+1,N)*PT(K)+QT(K)

  590 CONTINUE
C-----------------------------------------------
  391 CONTINUE
C**********************************************************
  999 CONTINUE
      call reset
      return
      end
C
C************************************************
      subroutine RESET
C************************************************
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/RESID/RMAX(13),IRESID
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      COMMON/SORC/SMAX,SSUM
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1         (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2         ,(F(1,1,1,5),T(1,1,1))
      DO 400 K=2,N2
      DO 400 J=2,M2
```

```
      DO 400 I=2,L2
      CON(I,J,K)=0.
      AP(I,J,K)=0.
  400 CONTINUE
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE FORM
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1     U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/RESID/RMAX(13),IRESID
      COMMON/SORC/SMAX,SSUM
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1      (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2      ,(F(1,1,1,5),T(1,1,1))
    1 FORMAT(15X,'COMPUTATION  IN  CARTESIAN  COORDINATES')
    2 FORMAT(15X,'COMPUTATION FOR AXISYMMETRIC SITUATION')
    3 FORMAT(15X,'COMPUTATION  IN  POLAR  COORDINATES')
    4 FORMAT(14X,40(1H*),//)
      return
      end
C
COME HERE TO CALCULATE GRIDS SPECIFICATION
```

```
C************************************************************
      subroutine GEOMET
C************************************************************
C
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1   U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/RESID/RMAX(13),IRESID
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      COMMON/SORC/SMAX,SSUM
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1         (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2        ,(F(1,1,1,5),T(1,1,1))
    1 FORMAT(15X,'COMPUTATION  IN  CARTESIAN  COORDINATES')
    2 FORMAT(15X,'COMPUTATION FOR AXISYMMETRIC SITUATION')
    3 FORMAT(15X,'COMPUTATION  IN  POLAR  COORDINATES')
    4 FORMAT(14X,40(1H*),//)
      L2=L1-1
      L3=L2-1
      M2=M1-1
      M3=M2-1
      N2=N1-1
      N3=N2-1
      X(1)=XU(2)
      DO 5 I=2,L2
    5 X(I)=0.5*(XU(I+1)+XU(I))
      X(L1)=XU(L1)
```

```
      Y(1)=YV(2)
      DO 10 J=2,M2
   10 Y(J)=0.5*(YV(J+1)+YV(J))
      Y(M1)=YV(M1)
      Z(1)=ZW(2)
      DO 7 K=2,N2
    7 Z(K)=0.5*(ZW(K+1)+ZW(K))
      Z(N1)=ZW(N1)
C-----
      DO 15 I=2,L1
   15 XDIF(I)=X(I)-X(I-1)
      DO 18 I=2,L2
   18 XCV(I)=XU(I+1)-XU(I)
      DO 20 I=3,L2
   20 XCVS(I)=XDIF(I)
      XCVS(3)=XCVS(3)+XDIF(2)
      XCVS(L2)=XCVS(L2)+XDIF(L1)
      DO 22 I=3,L3
      XCVI(I)=0.5*XCV(I)
   22 XCVIP(I)=XCVI(I)
      XCVIP(2)=XCV(2)
      XCVI(L2)=XCV(L2)
      DO 175 K=2,N1
  175 ZDIF(K)=Z(K)-Z(K-1)
      DO 178 K=2,N2
  178 ZCV(K)=ZW(K+1)-ZW(K)
      DO 270 K=3,N2
  270 ZCVS(K)=ZDIF(K)
      ZCVS(3)=ZCVS(3)+ZDIF(2)
      ZCVS(N2)=ZCVS(N2)+ZDIF(N1)
      DO 272 K=3,N3
      ZCVK(K)=0.5*ZCV(K)
  272 ZCVKP(K)=ZCVK(K)
      ZCVKP(2)=ZCV(2)
      ZCVK(N2)=ZCV(N2)
      DO 35 J=2,M1
   35 YDIF(J)=Y(J)-Y(J-1)
      DO 40 J=2,M2
   40 YCV(J)=YV(J+1)-YV(J)
      DO 45 J=3,M2
   45 YCVS(J)=YDIF(J)
      YCVS(3)=YCVS(3)+YDIF(2)
      YCVS(M2)=YCVS(M2)+YDIF(M1)
      DO 277 J=3,M3
      YCVJ(J)=0.5*YCV(J)
  277 YCVJP(J)=YCVJ(J)
      YCVJP(2)=YCV(2)
      YCVJ(M2)=YCV(M2)
      IF(MODE.NE.1) GO TO 55
      DO 52 J=1,M1
      RMN(J)=1.0
```

```
52 R(J)=1.0
   GO TO 56
55 DO 50 J=2,M1
50 R(J)=R(J-1)+YDIF(J)
   RMN(2)=R(1)
   DO 60 J=3,M2
60 RMN(J)=RMN(J-1)+YCV(J-1)
   RMN(M1)=R(M1)
56 CONTINUE
   DO 57 J=1,M1
   SX(J)=1.
   SXMN(J)=1.
   IF(MODE.NE.3) GO TO 57
   SX(J)=R(J)
   IF(J.NE.1) SXMN(J)=RMN(J)
57 CONTINUE
   DO 62 J=2,M2
   YCVR(J)=R(J)*YCV(J)
   ARX(J)=YCVR(J)
   IF(MODE.NE.3) GO TO 62
   ARX(J)=YCV(J)
62 CONTINUE
   DO 64 J=4,M3
64 YCVRS(J)=0.5*(R(J)+R(J-1))*YDIF(J)
   YCVRS(3)=0.5*(R(3)+R(1))*YCVS(3)
   YCVRS(M2)=0.5*(R(M1)+R(M3))*YCVS(M2)
   IF(MODE.NE.2) GO TO 67
   DO 65 J=3,M3
   ARXJ(J)=0.25*(1.+RMN(J)/R(J))*ARX(J)
65 ARXJP(J)=ARX(J)-ARXJ(J)
   GO TO 68
67 DO 66 J=3,M3
   ARXJ(J)=0.5*ARX(J)
66 ARXJP(J)=ARXJ(J)
68 ARXJP(2)=ARX(2)
   ARXJ(M2)=ARX(M2)
   DO 70 J=3,M3
   FV(J)=ARXJP(J)/ARX(J)
70 FVP(J)=1.-FV(J)
   DO 85 I=3,L2
   FX(I)=0.5*XCV(I-1)/XDIF(I)
85 FXM(I)=1.-FX(I)
   FX(2)=0.
   FXM(2)=1.
   FX(L1)=1.
   FXM(L1)=0.
   DO 90 J=3,M2
   FY(J)=0.5*YCV(J-1)/YDIF(J)
90 FYM(J)=1.-FY(J)
   FY(2)=0.
   FYM(2)=1.
```

```
      FY(M1)=1.
      FYM(M1)=0.
      DO 87 K=3,N2
      FZ(K)=0.5*ZCV(K-1)/ZDIF(K)
   87 FZM(K)=1.-FZ(K)
      FZ(2)=0.
      FZM(2)=1.
      FZ(N1)=1.
      FZM(N1)=0.
C     CON,AP,U,V,RHO,PC AND P ARRAYS ARE INITIALIZED HERE
      DO 95 K=1,N1
      DO 95 J=1,M1
      DO 95 I=1,L1
      U(I,J,K)=0.
      V(I,J,K)=0.
      W(I,J,K)=0.
      DU(I,J,K)=0.
      DV(I,J,K)=0.
      DW(I,J,K)=0.
      CON(I,J,K)=0.
      AP(I,J,K)=0.
      RHO(I,J,K)=RHOCON
      P(I,J,K)=0.
      AIP(I,J,K)=0.
      AJP(I,J,K)=0.
      AKP(I,J,K)=0.
      AIM(I,J,K)=0.
      AJM(I,J,K)=0.
      AKM(I,J,K)=0.
      PC(I,J,K)=0.
      CON(I,J,K)=0.
   95 CONTINUE
      IF(MODE.EQ.1) PRINT 1
      IF(MODE.EQ.2) PRINT 2
      IF(MODE.EQ.3) PRINT 3
      PRINT 4
      RETURN
      end
C
C     COME HERE TO CALCUALTE COEFFICIENTS FOR FINITE DIFF. EQNS.
C************************************************************
      subroutine COEFF
C************************************************************
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
```

```
   6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
   7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
   8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
    COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
   1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
   2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
    COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
   1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
   2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
   3IST,JST,KST,ITER,LAST,
   4IPREF,JPREF,KPREF,MODE
    COMMON/HEADIN/TITLE
    CHARACTER*10 TITLE(13)
    COMMON/CNTL/LSTOP,ICALL,ISTOP
    COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
   1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
    COMMON/RESID/RMAX(13),IRESID
    common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
    COMMON/SORC/SMAX,SSUM
    COMMON/COEF/FLOW,DIFF,ACOF
    DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
    DIMENSION T(35,25,35)
    EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
   1        (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
   2        ,(F(1,1,1,5),T(1,1,1))
C
C  START OF ITERATION LOOP FOR EACH TIMESTEP
C
****************
***************
 99  CONTINUE
    ICALL=1
C
C  CALL UCOF, VCOF, AND WCOF TO FIND UHAT,VHAT,WHAT
    CALL UCOF
    CALL VCOF
    CALL WCOF
C
C  CALL PCOF TO CALCULATE PRESSURE EQN. COEF.
    IF(.NOT.LSOLVE(NF)) GO TO 500
    CALL PCOF
    IF(ITER.LE.1) GO TO 409
    DO 408 K=2,N2
    DO 408 J=2,M2
    DO 408 I=2,L2
    AP(I,J,K)=AP(I,J,K)/RELAX(NP)
    CON(I,J,K)=CON(I,J,K)+(1.-RELAX(NP))*AP(I,J,K)*P(I,J,K)
 408 CONTINUE
 409 CONTINUE
NF=4
    CALL TDMA
```

```
C
C  CALCULATE U*
C
   ICALL=2
   CALL UCOF
   NF=1
   IST=3
   JST=2
   KST=2
   DO 413 K=2,N2
   DO 413 J=2,M2
   DO 413 I=3,L2
 413 CON(I,J,K)=CON(I,J,K)+DU(I,J,K)*AP(I,J,K)*(P(I-1,J,K)-P(I,J,K))
C
C  SAVE OLD VALUES OF U FOR CONVERGENCE CHECKING
C
    DO 704 I=1,L1
DO 704 J=1,M1
 DO 704 K=1,N1
  UOLD(I,J,K)=U(I,J,K)
 704  CONTINUE
C
   CALL TDMA
C
C  CALCULATE V*
C
   CALL VCOF
   NF=2
   IST=2
   JST=3
   KST=2
   DO 513 K=2,N2
   DO 513 I=2,L2
   DO 513 J=3,M2
   CON(I,J,K)=CON(I,J,K)+DV(I,J,K)*AP(I,J,K)*(P(I,J-1,K)-P(I,J,K))
 513 continue
C  SAVE OLD VALUES OF V FOR CONVERGENCE CHECKING (TEMP STORE IN VHAT)
C
    DO 714 I=1,L1
DO 714 J=1,M1
 DO 714 K=1,N1
  VHAT(I,J,K)=V(I,J,K)
 714  CONTINUE
   CALL TDMA
C
C  CALCULATE W*
C
   CALL WCOF
   NF=3
   IST=2
   JST=2
```

```
      KST=3
      DO 523 J=2,M2
      DO 523 I=2,L2
      DO 523 K=3,N2
      CON(I,J,K)=CON(I,J,K)+DW(I,J,K)*AP(I,J,K)*(P(I,J,K-1)-P(I,J,K))
523   continue

C
C SAVE OLD VALUES OF W FOR CONVERGENCE CHECKING (TEMP STORE IN WHAT)
C
       DO 724 I=1,L1
       DO 724 J=1,M1
      DO 724 K=1,N1
     WHAT(I,J,K)=W(I,J,K)
 724  CONTINUE
      CALL TDMA
C
COEFFICIENTS FOR THE PRESSURE CORRECTION EQUATION———
C
      CALL PCOF
      NF=4
      IF(.NOT.LSOLVE(NF)) GO TO 500
      IST=2
      JST=2
      KST=2
      CALL DIFFUS
      SMAX=0.
      SSUM=0.
C     WRITE(*,*) ' P: COEFF 2'
      DO 410 K=2,N2
      DO 410 J=2,M2
      DO 410 I=2,L2
      VOL=YCV(J)*XCV(I)*ZCV(K)
 410 CON(I,J,K)=CON(I,J,K)*VOL
      DO 701 K=2,N2
      DO 701 J=2,M2
       CON(2,J,K)=RHO(1,J,K)*U(2,J,K)*YCV(J)*ZCV(K)
 701  CONTINUE
      DO 702 I=2,L2
      DO 702 K=2,N2
       CON(I,2,K)=RHO(I,1,K)*V(I,2,K)*XCV(I)*ZCV(K)
 702  CONTINUE
      DO 153 I=2,L2
      DO 153 J=2,M2
       CON(I,J,2)=RHO(I,J,1)*W(I,J,2)*XCV(I)*YCV(J)
 153  CONTINUE
C
c     WRITE(*,*) ' P: COEFF 3'
      DO 351 K=2,N2
      DO 351 J=2,M2
      DO 351 I=2,L2
```

```
      AREA=YCV(J)*ZCV(K)
      ARHO=AREA*(FX(I+1)*RHO(I+1,J,K)+FXM(I+1)*RHO(I,J,K))
      FLOW=ARHO*U(I+1,J,K)
      CON(I,J,K)=CON(I,J,K)-FLOW
      CON(I+1,J,K)=CON(I+1,J,K)+FLOW
C
      AREA=XCV(I)*ZCV(K)
      ARHO=AREA*(FY(J+1)*RHO(I,J+1,K)+FYM(J+1)*RHO(I,J,K))
      FLOW=ARHO*V(I,J+1,K)
      CON(I,J,K)=CON(I,J,K)-FLOW
      CON(I,J+1,K)=CON(I,J+1,K)+FLOW
C
      AREA=XCV(I)*YCV(J)
      ARHO=AREA*(FZ(K+1)*RHO(I,J,K+1)+FZM(K+1)*RHO(I,J,K))
      FLOW=ARHO*W(I,J,K+1)
      CON(I,J,K)=CON(I,J,K)-FLOW
      CON(I,J,K+1)=FLOW
      PC(I,J,K)=0.
 351  CONTINUE
      DO 352 I=2,L2
      DO 352 J=2,M2
      DO 352 K=2,N2
      SMAX=AMAX1(SMAX,ABS(CON(I,J,K)))
      SSUM=SSUM+CON(I,J,K)
 352  CONTINUE
      CALL TDMA
C
COME HERE TO CORRECT THE VELOCITIES——————
C
C     WRITE(*,*) ' VEL CORREC '
      DO 511 K=2,N2
      DO 511 J=2,M2
      DO 511 I=2,L2
      IF(I.NE.2) U(I,J,K)=U(I,J,K)+DU(I,J,K)*(PC(I-1,J,K)-PC(I,J,K))
      IF(J.NE.2) V(I,J,K)=V(I,J,K)+DV(I,J,K)*(PC(I,J-1,K)-PC(I,J,K))
      IF(K.NE.2) W(I,J,K)=W(I,J,K)+DW(I,J,K)*(PC(I,J,K-1)-PC(I,J,K))
 511  CONTINUE
 500  CONTINUE
C     WRITE(*,*) ' T COEFF 1 '
C
COEFFICIENTS FOR OTHER EQUATIONS——————————
C
      CALL RESET
      IST=2
      JST=2
      KST=2
      DO 600 NF=5,NFMAX
      IF(.NOT.LSOLVE(NF)) GO TO 600
      CALL DIFFUS
      REL=1.-RELAX(NF)
      DO 601 I=2,L2
```

```
      DO 601 J=2,M2
      DO 601 K=2,N2
COEFFICIENTS AWEST AND AEAST
      AREA= YCV(J)*ZCV(K)
      FLOW=AREA*U(I+1,J,K)*(FX(I+1)*RHO(I+1,J,K)+FXM(I+1)*RHO(I,J,K))
      DIFF=AREA*2.*GAM(I,J,K)*GAM(I+1,J,K)/(XCV(I)*GAM(I+1,J,K)+
     1 XCV(I+1)*GAM(I,J,K)+1.0E-20)
      CALL PROFIL
      IF(ABS(FLOW).LT.1E-20) FLOW=0.
      AIM(I+1,J,K)=ACOF+AMAX1(ZERO,FLOW)
      AIP(I,J,K)=AIM(I+1,J,K)-FLOW
COEFFICIENTS ANORTH AND ASOUTH
      AREA= XCV(I)*ZCV(K)
      FLOW=AREA*V(I,J+1,K)*(FY(J+1)*RHO(I,J+1,K)+FYM(J+1)*RHO(I,J,K))
      DIFF=AREA*2.*GAM(I,J,K)*GAM(I,J+1,K)/(YCV(J)*GAM(I,J+1,K)+
     1 YCV(J+1)*GAM(I,J,K)+1.0E-20)
      CALL PROFIL
      AJM(I,J+1,K)=ACOF+AMAX1(ZERO,FLOW)
      AJP(I,J,K)=AJM(I,J+1,K)-FLOW
COEFFICIENTS AOUT AND AINTO
      AREA= YCV(J)*XCV(I)
      FLOW=AREA*W(I,J,K+1)*(FZ(K+1)*RHO(I,J,K+1)+FZM(K+1)*RHO(I,J,K))
      DIFF=AREA*2.*GAM(I,J,K)*GAM(I,J,K+1)/(ZCV(K)*GAM(I,J,K+1)+
     1 ZCV(K+1)*GAM(I,J,K)+1.0E-20)
      CALL PROFIL
      IF(ABS(FLOW).LT.1E-20) FLOW=0.
      AKM(I,J,K+1)=ACOF+AMAX1(ZERO,FLOW)
      AKP(I,J,K)=AKM(I,J,K+1)-FLOW
  601 CONTINUE
C     WRITE(*,*) ' T COEFF 2 '
      DO 610 J=2,M2
      DO 610 K=2,N2
COEFFICIENTS AWEST AND AEAST
      AREA=YCV(J)*ZCV(K)
      FLOW=AREA*U(2,J,K)*RHO(1,J,K)
      DIFF=AREA*GAM(1,J,K)/XDIF(2)
      CALL PROFIL
      IF(ABS(FLOW).LT.1E-20) FLOW=0.
      AIM(2,J,K)=ACOF+AMAX1(ZERO,FLOW)
      FLOW=AREA*U(L1,J,K)*RHO(L1,J,K)
      DIFF=AREA*GAM(L1,J,K)/XDIF(L1)
      CALL PROFIL
      AIP(L2,J,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  610 CONTINUE
C     WRITE(*,*) ' T COEFF 3 '
      DO 611 I=2,L2
      DO 611 K=2,N2
COEFFICIENTS ANORTH AND ASOUTH
      AREA= XCV(I)*ZCV(K)
      FLOW=AREA*V(I,2,K)*RHO(I,1,K)
      DIFF=AREA*GAM(I,1,K)/YDIF(2)
```

```
      CALL PROFIL
      AJM(I,2,K)=ACOF+AMAX1(ZERO,FLOW)
      FLOW=AREA*V(I,M1,K)*RHO(I,M1,K)
      DIFF=AREA*GAM(I,M1,K)/YDIF(M1)
      CALL PROFIL
      AJP(I,M2,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  611 CONTINUE
C     WRITE(*,*) ' T COEFF 4 '
      DO 612 I=2,L2
      DO 612 J=2,M2
COEFFICIENTS AOUT AND AINTO
      AREA= YCV(J)*XCV(I)
      FLOW=AREA*W(I,J,2)*RHO(I,J,1)
      DIFF=AREA*GAM(I,J,1)/ZDIF(2)
      CALL PROFIL
      AKM(I,J,2)=ACOF+AMAX1(ZERO,FLOW)
      FLOW=AREA*W(I,J,N1)*RHO(I,J,N1)
      DIFF=AREA*GAM(I,J,N1)/ZDIF(N1)
      CALL PROFIL
      AKP(I,J,N2)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  612 CONTINUE
C     WRITE(*,*) ' T COEFF 5 '
      DO 3987 I=1,L1
      DO 3987 J=1,M1
      DO 3987 K=1,N1
      VOL=YCV(J)*XCV(I)*ZCV(K)
      APT=RHO(I,J,K)/DT
      AP(I,J,K)=AP(I,J,K)-APT
      CON(I,J,K)=CON(I,J,K)+APT*T0(I,J,K)
      AP(I,J,K)=(-AP(I,J,K)*VOL+AIP(I,J,K)+AIM(I,J,K)
     1 +AJP(I,J,K)+AJM(I,J,K)+AKM(I,J,K)+AKP(I,J,K))
     2 /RELAX(NF)
      ap1(i,j,k)=ap(i,j,k)

      CON(I,J,K)=CON(I,J,K)*VOL+REL*AP(I,J,K)*F(I,J,K,NF)

C
C  SAVE OLD VALUES OF T FOR CONVERGENCE CHECKING
C
       TOLD(I,J,K)=T(I,J,K)
 3987  CONTINUE
*******************************************************
      CALL TDMA
C
********************************************************************************
  600 CONTINUE
********************************************************************************
C  CHECK FOR CONVERGENCE IN THIS TIME STEP
C  CONVERGENCE BASED ON CHANGE IN TEMPERATURE BETWEEN SUCCESSIVE
C  ITERATIONS AND ON OVERALL ENERGY BALANCE
C
```

```
    ICONV=0
    IF(ITER1.EQ.1) THEN
 ITER1=ITER1+1
    ELSE
 C  FIND MAXIMUM VALUES FOR THIS ITERATION
 TMX=0.0
 UMX=0.0
 VMX=0.0
 WMX=0.0
 DO 689 I=1,L1
  DO 689 J=1,M1
   DO 689 K=1,N1
    TMX=AMAX1(ABS(T(I,J,K)),TMX)
    UMX=AMAX1(ABS(U(I,J,K)),UMX)
    VMX=AMAX1(ABS(V(I,J,K)),VMX)
    WMX=AMAX1(ABS(W(I,J,K)),WMX)
  689   CONTINUE
 DELTMX=0.0
 DO 690 I=2,L2
 DO 690 J=2,M2
 DO 690 K=2,N2
 C CALCULATE RELATIVE CHANGE IN TEMP FROM LAST ITERATION
  DELT=ABS((T(I,J,K)-TOLD(I,J,K))/TMX)
  DELU=ABS((U(I,J,K)-UOLD(I,J,K))/UMX)
 c      DELV=ABS((V(I,J,K)-VOLD(I,J,K))/VMX)
 c      DELW=ABS((W(I,J,K)-WOLD(I,J,K))/WMX)
  DELTMX=AMAX1(DELTMX,DELT)
  DELUMX=AMAX1(DELUMX,DELU)
 c      DELVMX=AMAX1(DELVMX,DELV)
 c      DELWMX=AMAX1(DELWMX,DELW)
   690   CONTINUE
 if(time.gt.0.4.and.iter1.gt.100)go to 1023
 IF(DELTMX.GT.EPST) GOTO 691
 c     if(iter1.le.20)go to 691
 C  CHECK ENERGY BALANCE AFTER DELTMX CRITERIA MET
 CALL NRGBAL
 IF(ABS(ENBAL).LE.1.5) THEN
  1023   ICONV=1
  ITERL=ITER1
  ITER1=0
 ENDIF
   691   ITER1=ITER1+1
      IF(ABS(ENBAL).GE.200) THEN
 C  ITERATIONS ARE DIVERGING: TERMINATE RUN
       WRITE(*,*) ' DIVERGING ITERATIONS: RUN TERMINATED'
       WRITE(*,*) ' TRY SMALLER RELAXATION FACTORS'
       STOP
      ENDIF
      IF(ITER1.GT.10000) THEN
      CALL NRGBAL
 c     WRITE(4,*) X,Y,Z,XU,YV,ZW,U0,V0,W0,P,T0
```

```
      WRITE(*,*) ' EXCEEDED MAX NUMBER OF ITERATIONS PER TIME STEP'
      WRITE(*,*) ' PROGRAM TERMINATING'
      WRITE(*,*) ' TIME=',TIME
      WRITE(*,*) ' DELTMX=',DELTMX, ' ENBAL =',ENBAL
      STOP
     ENDIF
    ENDIF
CALL NRGBAL
c   WRITE(13,*) ITER1,DELTMX,DELUMX,DELVMX,DELWMX,ENBAL
    IF(ICONV.EQ.0) THEN
C TIME STEP IS NOT CONVERGED: UPDATE BOUNDARY CONDITIONS AND ITERATE
    print*,'TIME= ',TIME,' DELTMX: ',DELTMX
    print*,'ENBAL: ',ENBAL,' ITER1: ',ITER1
    print*,T(4,5,6),T(12,7,9),T(7,13,15)
CALL BNDRY
GOTO 99
    ENDIF
C TIME STEP IS CONVERGED: INCREMENT TIME AND ITERATION COUNTERS
 100 TIME=TIME+DT
    ITER=ITER+1
    IF(TIME.GE.TLAST)
    1 LSTOP=.TRUE.
    RETURN
    end
C
C *********************************************************************
     subroutine INCRV
C
    LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
    COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
    1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
    2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
     COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
    3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
    4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
    5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
    6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
    7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
    8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
     COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
    1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
    2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
     COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
    1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
    2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
    3IST,JST,KST,ITER,LAST,
    4IPREF,JPREF,KPREF,MODE
     COMMON/HEADIN/TITLE
     CHARACTER*10 TITLE(13)
     COMMON/CNTL/LSTOP,ICALL,ISTOP
     COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
```

```
   1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
    COMMON/RESID/RMAX(13),IRESID
    common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
    COMMON/SORC/SMAX,SSUM
    COMMON/COEF/FLOW,DIFF,ACOF
    DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
    DIMENSION T(35,25,35)
    EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
   1        (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
   2        ,(F(1,1,1,5),T(1,1,1))
C
C  TIME STEP IS CONVERGED: INCREMENT VARIABLE ARRAYS
    rewind(7)
    DO 700 I=1,L1
    DO 700 J=1,M1
    DO 700 K=1,N1
     T0(I,J,K)=T(I,J,K)
     U0(I,J,K)=U(I,J,K)
     V0(I,J,K)=V(I,J,K)
     W0(I,J,K)=W(I,J,K)
     delh0(i,j,k)=delh(i,j,k)
     tprev(i,j,k)=t(i,j,k)
  700 CONTINUE
    WRITE(7,*) X,Y,Z,XU,YV,ZW,U,V,W,P,T
    RETURN
    END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
SUBROUTINE UCOF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
    LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
    COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
    1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
    2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
     COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
    3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
    4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
    5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
    6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
    7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
    8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
    COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
    1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
    2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
    COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
    1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
    2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
    3IST,JST,KST,ITER,LAST,
    4IPREF,JPREF,KPREF,MODE
     COMMON/HEADIN/TITLE
     CHARACTER*10 TITLE(13)
     COMMON/CNTL/LSTOP,ICALL,ISTOP
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      COMMON/RESID/RMAX(13),IRESID
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1  U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/SORC/SMAX,SSUM
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1       (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2       ,(F(1,1,1,5),T(1,1,1))
C
C ***********************************************************************
c    ENTRY UCOF
C
COEFFICIENTS FOR THE U EQUATION
C
      CALL RESET
      NF=1
      IF(.NOT.LSOLVE(NF)) GO TO 100
      IST=3
      JST=2
      KST=2
      CALL DIFFUS

      REL=1.-RELAX(NF)
C     WRITE(21,*) ' U: COEFF 1'
      DO 103 I=3,L2
      DO 103 J=2,M2
      DO 103 K=2,N2
COEFFICIENTS AEAST AND AWEST
      FL=U(I,J,K)*(FX(I)*RHO(I,J,K)+FXM(I)*RHO(I-1,J,K))
      FLP=U(I+1,J,K)*(FX(I+1)*RHO(I+1,J,K)+FXM(I+1)*RHO(I,J,K))
      FLOW=YCV(J)*ZCV(K)*0.5*(FL+FLP)
      DIFF=YCV(J)*ZCV(K)*GAM(I,J,K)/XCV(I)
      CALL PROFIL
      AIM(I+1,J,K)=ACOF+AMAX1(ZERO,FLOW)
      AIP(I,J,K)=AIM(I+1,J,K)-FLOW
COEFFICIENTS ANORTH AND ASOUTH
      FL=XCVI(I)*V(I,J+1,K)*(FY(J+1)*RHO(I,J+1,K)+FYM(J+1)*RHO(I,J,K))
      FLM=XCVIP(I-1)*V(I-1,J+1,K)*(FY(J+1)*RHO(I-1,J+1,K)+FYM(J+1)*
     1 RHO(I-1,J,K))
      GM=GAM(I,J,K)*GAM(I,J+1,K)
     1 /(YCV(J)*GAM(I,J+1,K)+YCV(J+1)*GAM(I,J,K)+
     2 1.0E-20)*XCVI(I)
      GMM=GAM(I-1,J,K)*GAM(I-1,J+1,K)
     1  /(YCV(J)*GAM(I-1,J+1,K)+YCV(J+1)*
     2 GAM(I-1,J,K)+1.E-20)*XCVIP(I-1)
      DIFF=ZCV(K)*2.*(GM+GMM)
      FLOW=ZCV(K)*(FL+FLM)
      CALL PROFIL
```

```
      AJM(I,J+1,K)=ACOF+AMAX1(ZERO,FLOW)
      AJP(I,J,K)=AJM(I,J+1,K)-FLOW
C COEFFICIENTS AIN   AND  AOUT
      FL=XCVI(I)*W(I,J,K+1)*(FZ(K+1)*RHO(I,J,K+1)+FZM(K+1)*RHO(I,J,K))
      FLM=XCVIP(I-1)*W(I-1,J,K+1)*(FZ(K+1)*RHO(I-1,J,K+1)+FZM(K+1)*
     1 RHO(I-1,J,K))
      GM=GAM(I,J,K)*GAM(I,J,K+1)
     1 /(ZCV(K)*GAM(I,J,K+1)+ZCV(K+1)*GAM(I,J,K)+
     2 1.0E-20)*XCVI(I)
      GMM=GAM(I-1,J,K)*GAM(I-1,J,K+1)
     1  /(ZCV(K)*GAM(I-1,J,K+1)+ZCV(K+1)*
     2 GAM(I-1,J,K)+1.E-20)*XCVIP(I-1)
      DIFF=YCV(J)*2.*(GM+GMM)
      FLOW=YCV(J)*(FL+FLM)
      CALL PROFIL
      AKM(I,J,K+1)=ACOF+AMAX1(ZERO,FLOW)
      AKP(I,J,K)=AKM(I,J,K+1)-FLOW
  103 CONTINUE
C    WRITE(*,*) ' U: COEFF 2'
      DO 104 J=2,M2
      DO 104 K=2,N2
C COEFFICIENTS AEAST AND AWEST
      AREA=YCV(J)*ZCV(K)
      FLOW=AREA*RHO(1,J,K)*U(2,J,K)
      DIFF=AREA*GAM(1,J,K)/XCV(2)
      CALL PROFIL
      AIM(3,J,K)=ACOF+AMAX1(ZERO,FLOW)
      FLOW=AREA*RHO(L1,J,K)*U(L1,J,K)
      DIFF=AREA*GAM(L1,J,K)/XCV(L2)
      CALL PROFIL
      AIP(L2,J,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  104 CONTINUE
C    WRITE(*,*) ' U: COEFF 3'
      DO 105 I=3,L2
      DO 105 K=2,N2
C COEFFICIENTS ANORTH AND ASOUTH
      FL=XCVI(I)*V(I,2,K)*RHO(I,1,K)
      FLM=XCVIP(I-1)*V(I-1,2,K)*RHO(I-1,1,K)
      FLOW=ZCV(K)*(FL+FLM)
      GM=XCVI(I)*GAM(I,1,K)+XCVIP(I-1)*GAM(I-1,1,K)
      DIFF=ZCV(K)*GM/YDIF(2)
      CALL PROFIL
      AJM(I,2,K)=ACOF+AMAX1(ZERO,FLOW)
      FL=XCVI(I)*V(I,M1,K)*RHO(I,M1,K)
      FLM=XCVIP(I-1)*V(I-1,M1,K)*RHO(I-1,M1,K)
      FLOW=ZCV(K)*(FL+FLM)
      GM=XCVI(I)*GAM(I,M1,K)+XCVIP(I-1)*GAM(I-1,M1,K)
      DIFF=ZCV(K)*GM/YDIF(M1)
      CALL PROFIL
      AJP(I,M2,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  105 CONTINUE
```

```
C    WRITE(*,*) ' U: COEFF 4'
     DO 106 I=3,L2
     DO 106 J=2,M2
COEFFICIENTS AIN AND AOUT
     FL=XCVI(I)*W(I,J,2)*RHO(I,J,1)
     FLM=XCVIP(I-1)*W(I-1,J,2)*RHO(I-1,J,1)
     FLOW=YCV(J)*(FL+FLM)
     GM=XCVI(I)*GAM(I,J,1)+XCVIP(I-1)*GAM(I-1,J,1)
     DIFF=YCV(J)*GM/ZDIF(2)
     CALL PROFIL
     AKM(I,J,2)=ACOF+AMAX1(ZERO,FLOW)
     FL=XCVI(I)*W(I,J,N1)*RHO(I,J,N1)
     FLM=XCVIP(I-1)*W(I-1,J,N1)*RHO(I-1,J,N1)
     FLOW=YCV(J)*(FL+FLM)
     GM=XCVI(I)*GAM(I,J,N1)+XCVIP(I-1)*GAM(I-1,J,N1)
     DIFF=YCV(J)*GM/ZDIF(N1)
     CALL PROFIL
     AKP(I,J,N2)=ACOF+AMAX1(ZERO,FLOW)-FLOW
106  CONTINUE
C    WRITE(*,*) ' U: COEFF 5'
      DO 107 I=3,L2
      DO 107 J=2,M2
      DO 107 K=2,N2
     VOL=YCV(J)*XCVS(I)*ZCV(K)
     APT=(RHO(I,J,K)*XCVI(I)+RHO(I-1,J,K)*XCVIP(I-1))
     1/(XCVS(I)*DT)
     AP(I,J,K)=AP(I,J,K)-APT
     CON(I,J,K)=CON(I,J,K)+APT*U0(I,J,K)
     AP(I,J,K)=
     1  (-AP(I,J,K)*VOL+AIP(I,J,K)+AIM(I,J,K)+AJP(I,J,K)+AJM(I,J,K)
     2  +AKP(I,J,K)+AKM(I,J,K))
     3/RELAX(NF)
***********************************************************source term
*******************************************************************
     CON(I,J,K)=CON(I,J,K)*VOL+REL*AP(I,J,K)*U(I,J,K)
     DU(I,J,K)=VOL/XDIF(I)
     DU(I,J,K)=DU(I,J,K)/AP(I,J,K)
 107 CONTINUE
     IF(ICALL.EQ.1) THEN
C______TEMPORARY USE OF PC(I,J) TO STORE UHAT___________
      DO 151 K=2,N2
      DO 151 J=2,M2
      DO 151 I=3,L2
     PC(I,J,K)=(AIP(I,J,K)*U(I+1,J,K)+AIM(I,J,K)*U(I-1,J,K)
     1        +AJP(I,J,K)*U(I,J+1,K)+AJM(I,J,K)*U(I,J-1,K)
     2        +AKP(I,J,K)*U(I,J,K+1)+AKM(I,J,K)*U(I,J,K-1)
     3        +CON(I,J,K))/AP(I,J,K)
 151 continue
endif
 100 CONTINUE
     RETURN
```

```
      end
C
C ***********************************************************************
      subroutine VCOF
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/RESID/RMAX(13),IRESID
      COMMON/SORC/SMAX,SSUM
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1        (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2        ,(F(1,1,1,5),T(1,1,1))
C
COEFFICIENTS FOR THE  V  EQUATION-------------
C
      CALL RESET
      NF=2
      IF(.NOT.LSOLVE(NF)) GO TO 200
      IST=2
      JST=3
      KST=2
      CALL DIFFUS
      REL=1.-RELAX(NF)
C     WRITE(*,*) ' V: COEFF 1'
      DO 203 J=3,M2
      DO 203 I=2,L2
```

```
      DO 203 K=2,N2
C COEFFICIENTS ANORTH AND ASOUTH
      FL=V(I,J,K)*(FY(J)*RHO(I,J,K)+FYM(J)*RHO(I,J-1,K))
      FLP=V(I,J+1,K)*(FY(J+1)*RHO(I,J+1,K)+FYM(J+1)*RHO(I,J,K))
      FLOW=XCV(I)*ZCV(K)*0.5*(FL+FLP)
      DIFF=XCV(I)*ZCV(K)*GAM(I,J,K)/YCV(J)
      CALL PROFIL
      AJM(I,J+1,K)=ACOF+AMAX1(ZERO,FLOW)
      AJP(I,J,K)=AJM(I,J+1,K)-FLOW
C COEFFICIENTS AEAST AND AWEST
      FL=YCVJ(J)*U(I+1,J,K)*(FX(I+1)*RHO(I+1,J,K)+FXM(I+1)*RHO(I,J,K))
      FLM=YCVJP(J-1)*U(I+1,J-1,K)*(FX(I+1)*RHO(I+1,J-1,K)+FXM(I+1)*
     1 RHO(I,J-1,K))
      GM=GAM(I,J,K)*GAM(I+1,J,K)
     1 /(XCV(I)*GAM(I+1,J,K)+XCV(I+1)*GAM(I,J,K)+
     2 1.0E-20)*YCVJ(J)
      GMM=GAM(I,J-1,K)*GAM(I+1,J-1,K)
     1  /(XCV(I)*GAM(I+1,J-1,K)+XCV(I+1)*
     2 GAM(I,J-1,K)+1.E-20)*YCVJP(J-1)
      DIFF=ZCV(K)*2.*(GM+GMM)
      FLOW=ZCV(K)*(FL+FLM)
      CALL PROFIL
      AIM(I+1,J,K)=ACOF+AMAX1(ZERO,FLOW)
      AIP(I,J,K)=AIM(I+1,J,K)-FLOW
C COEFFICIENTS AIN   AND  AOUT
      FL=YCVJ(J)*W(I,J,K+1)*(FZ(K+1)*RHO(I,J,K+1)+FZM(K+1)*RHO(I,J,K))
      FLM=YCVJP(J-1)*W(I,J-1,K+1)*(FZ(K+1)*RHO(I,J-1,K+1)+FZM(K+1)*
     1 RHO(I,J-1,K))
      GM=GAM(I,J,K)*GAM(I,J,K+1)
     1 /(ZCV(K)*GAM(I,J,K+1)+ZCV(K+1)*GAM(I,J,K)+
     2 1.0E-20)*YCVJ(J)
      GMM=GAM(I,J-1,K)*GAM(I,J-1,K+1)
     1  /(ZCV(K)*GAM(I,J-1,K+1)+ZCV(K+1)*
     2 GAM(I,J-1,K)+1.E-20)*YCVJP(J-1)
      DIFF=XCV(I)*2.*(GM+GMM)
      FLOW=XCV(I)*(FL+FLM)
      CALL PROFIL
      AKM(I,J,K+1)=ACOF+AMAX1(ZERO,FLOW)
      AKP(I,J,K)=AKM(I,J,K+1)-FLOW
  203 CONTINUE
C     WRITE(*,*) ' V: COEFF 2'
      DO 204 I=2,L2
      DO 204 K=2,N2
C COEFFICIENTS ANORTH AND ASOUTH
      AREA=XCV(I)*ZCV(K)
      FLOW=AREA*RHO(I,1,K)*V(I,2,K)
      DIFF=AREA*GAM(I,1,K)/YCV(2)
      CALL PROFIL
      AJM(I,3,K)=ACOF+AMAX1(ZERO,FLOW)
      FLOW=AREA*RHO(I,M1,K)*V(I,M1,K)
      DIFF=AREA*GAM(I,M1,K)/YCV(M2)
```

```
      CALL PROFIL
      AJP(I,M2,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
204   CONTINUE
C     WRITE(*,*) ' V: COEFF 3'
      DO 205 J=3,M2
      DO 205 K=2,N2
COEFFICIENTS AEAST AND AWEST
      FL=YCVJ(J)*U(2,J,K)*RHO(1,J,K)
      FLM=YCVJP(J-1)*U(2,J-1,K)*RHO(1,J-1,K)
      FLOW=ZCV(K)*(FL+FLM)
      GM=YCVJ(J)*GAM(1,J,K)+YCVJP(J-1)*GAM(1,J-1,K)
      DIFF=ZCV(K)*GM/XDIF(2)
      CALL PROFIL
      AIM(2,J,K)=ACOF+AMAX1(ZERO,FLOW)
      FL=YCVJ(J)*U(L1,J,K)*RHO(L1,J,K)
      FLM=YCVJP(J-1)*U(L1,J-1,K)*RHO(L1,J-1,K)
      FLOW=ZCV(K)*(FL+FLM)
      GM=YCVJ(J)*GAM(L1,J,K)+YCVJP(J-1)*GAM(L1,J-1,K)
      DIFF=ZCV(K)*GM/XDIF(L1)
      CALL PROFIL
      AIP(L2,J,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
205   CONTINUE
C     WRITE(*,*) ' V: COEFF 4'
      DO 206 I=2,L2
      DO 206 J=3,M2
COEFFICIENTS AIN AND AOUT
      FL=YCVJ(J)*W(I,J,2)*RHO(I,J,1)
      FLM=YCVJP(J-1)*W(I,J-1,2)*RHO(I,J-1,1)
      FLOW=XCV(I)*(FL+FLM)
      GM=YCVJ(J)*GAM(I,J,1)+YCVJP(J-1)*GAM(I,J-1,1)
      DIFF=XCV(I)*GM/ZDIF(2)
      CALL PROFIL
      AKM(I,J,2)=ACOF+AMAX1(ZERO,FLOW)
      FL=YCVJ(J)*W(I,J,N1)*RHO(I,J,N1)
      FLM=YCVJP(J-1)*W(I,J-1,N1)*RHO(I,J-1,N1)
      FLOW=XCV(I)*(FL+FLM)
      GM=YCVJ(J)*GAM(I,J,N1)+YCVJP(J-1)*GAM(I,J-1,N1)
      DIFF=XCV(I)*GM/ZDIF(N1)
      CALL PROFIL
      AKP(I,J,N2)=ACOF+AMAX1(ZERO,FLOW)-FLOW
206   CONTINUE
C     WRITE(*,*) ' V: COEFF 5'
      DO 207 I=2,L2
      DO 207 J=3,M2
      DO 207 K=2,N2
      VOL=XCV(I)*YCVS(J)*ZCV(K)
      APT=(RHO(I,J,K)*YCVJ(J)+RHO(I,J-1,K)*YCVJP(J-1))
     1/(YCVS(J)*DT)
      AP(I,J,K)=AP(I,J,K)-APT
      CON(I,J,K)=CON(I,J,K)+APT*V0(I,J,K)
      AP(I,J,K)=
```

```
     1  (-AP(I,J,K)*VOL+AIP(I,J,K)+AIM(I,J,K)+AJP(I,J,K)+AJM(I,J,K)
     2  +AKP(I,J,K)+AKM(I,J,K))
     3/RELAX(NF)
*******************************************************source term
*****************************************************************
      CON(I,J,K)=CON(I,J,K)*VOL+REL*AP(I,J,K)*V(I,J,K)
      DV(I,J,K)=VOL/YDIF(J)
      DV(I,J,K)=DV(I,J,K)/AP(I,J,K)
 207 CONTINUE
      IF(ICALL.EQ.1) THEN
       DO 8099 I=2,L2
       DO 8099 K=2,N2
       DO 8099 J=3,M2
8099    VHAT(I,J,K)=(AIP(I,J,K)*V(I+1,J,K)+AIM(I,J,K)*V(I-1,J,K)
     1      +AJP(I,J,K)*V(I,J+1,K)+AJM(I,J,K)*V(I,J-1,K)
     2      +AKP(I,J,K)*V(I,J,K+1)+AKM(I,J,K)*V(I,J,K-1)
     3      +CON(I,J,K))/AP(I,J,K)
      ENDIF
 200 CONTINUE
      RETURN
      end
C
C ********************************************************************
      subroutine WCOF
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1  U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/RESID/RMAX(13),IRESID
      COMMON/SORC/SMAX,SSUM
      COMMON/COEF/FLOW,DIFF,ACOF
```

```
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1      (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2      ,(F(1,1,1,5),T(1,1,1))
C
COEFFICIENTS FOR THE W EQUATION-----------------------
C
      CALL RESET
      NF=3
      IF(.NOT.LSOLVE(NF)) GO TO 300
      IST=2
      JST=2
      KST=3
      CALL DIFFUS
      REL=1.-RELAX(NF)
C     WRITE(*,*) ' W: COEFF 1'
      DO 303 K=3,N2
      DO 303 J=2,M2
      DO 303 I=2,L2
COEFFICIENTS AIN  AND AOUT
      FL=W(I,J,K)*(FZ(K)*RHO(I,J,K)+FZM(K)*RHO(I,J,K-1))
      FLP=W(I,J,K+1)*(FZ(K+1)*RHO(I,J,K+1)+FZM(K+1)*RHO(I,J,K))
      FLOW=YCV(J)*XCV(I)*0.5*(FL+FLP)
      DIFF=YCV(J)*XCV(I)*GAM(I,J,K)/ZCV(K)
      CALL PROFIL
      AKM(I,J,K+1)=ACOF+AMAX1(ZERO,FLOW)
      AKP(I,J,K)=AKM(I,J,K+1)-FLOW
COEFFICIENTS ANORTH AND ASOUTH
      FL=ZCVK(K)*V(I,J+1,K)*(FY(J+1)*RHO(I,J+1,K)+FYM(J+1)*RHO(I,J,K))
      FLM=ZCVKP(K-1)*V(I,J+1,K-1)*(FY(J+1)*RHO(I,J+1,K-1)+FYM(J+1)*
     1 RHO(I,J,K-1))
      GM=GAM(I,J,K)*GAM(I,J+1,K)
     1 /(YCV(J)*GAM(I,J+1,K)+YCV(J+1)*GAM(I,J,K)+
     2 1.0E-20)*ZCVK(K)
      GMM=GAM(I,J,K-1)*GAM(I,J+1,K-1)
     1  /(YCV(J)*GAM(I,J+1,K-1)+YCV(J+1)*
     2 GAM(I,J,K-1)+1.E-20)*ZCVKP(K-1)
      DIFF=XCV(I)*2.*(GM+GMM)
      FLOW=XCV(I)*(FL+FLM)
      CALL PROFIL
      AJM(I,J+1,K)=ACOF+AMAX1(ZERO,FLOW)
      AJP(I,J,K)=AJM(I,J+1,K)-FLOW
COEFFICIENTS AEAST  AND  AWEST
      FL=ZCVK(K)*U(I+1,J,K)*(FX(I+1)*RHO(I+1,J,K)+FXM(I+1)*RHO(I,J,K))
      FLM=ZCVKP(K-1)*U(I+1,J,K-1)*(FX(I+1)*RHO(I+1,J,K-1)+FXM(I+1)*
     1 RHO(I,J,K-1))
      GM=GAM(I,J,K)*GAM(I+1,J,K)
     1 /(XCV(I)*GAM(I+1,J,K)+XCV(I+1)*GAM(I,J,K)+
     2 1.0E-20)*ZCVK(K)
```

```
      GMM=GAM(I,J,K-1)*GAM(I+1,J,K-1)
     1 /(XCV(I)*GAM(I+1,J,K-1)+XCV(I+1)*
     2 GAM(I,J,K-1)+1.E-20)*ZCVKP(K-1)
      DIFF=YCV(J)*2.*(GM+GMM)
      FLOW=YCV(J)*(FL+FLM)
      CALL PROFIL
      AIM(I+1,J,K)=ACOF+AMAX1(ZERO,FLOW)
      AIP(I,J,K)=AIM(I+1,J,K)-FLOW
  303 CONTINUE
C     WRITE(*,*) ' W: COEFF 2'
      DO 304 J=2,M2
      DO 304 I=2,L2
COEFFICIENTS AIN  AND AOUT
      AREA=YCV(J)*XCV(I)
      FLOW=AREA*RHO(I,J,1)*W(I,J,2)
      DIFF=AREA*GAM(I,J,1)/ZCV(2)
      CALL PROFIL
      AKM(I,J,3)=ACOF+AMAX1(ZERO,FLOW)
      FLOW=AREA*RHO(I,J,N1)*W(I,J,N1)
      DIFF=AREA*GAM(I,J,N1)/ZCV(N2)
      CALL PROFIL
      AKP(I,J,N2)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  304 CONTINUE
C     WRITE(*,*) ' W: COEFF 3'
      DO 305 I=2,L2
      DO 305 K=3,N2
COEFFICIENTS ANORTH AND ASOUTH
      FL=ZCVK(K)*V(I,2,K)*RHO(I,1,K)
      FLM=ZCVKP(K-1)*V(I,2,K-1)*RHO(I,1,K-1)
      FLOW=XCV(I)*(FL+FLM)
      GM=ZCVK(K)*GAM(I,1,K)+ZCVKP(K-1)*GAM(I,1,K-1)
      DIFF=XCV(I)*GM/YDIF(2)
      CALL PROFIL
      AJM(I,2,K)=ACOF+AMAX1(ZERO,FLOW)
      FL=ZCVK(K)*V(I,M1,K)*RHO(I,M1,K)
      FLM=ZCVKP(K-1)*V(I,M1,K-1)*RHO(I,M1,K-1)
      FLOW=XCV(I)*(FL+FLM)
      GM=ZCVK(K)*GAM(I,M1,K)+ZCVKP(K-1)*GAM(I,M1,K-1)
      DIFF=XCV(I)*GM/YDIF(M1)
      CALL PROFIL
      AJP(I,M2,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
  305 CONTINUE
C     WRITE(*,*) ' W: COEFF 4'
      DO 306 K=3,N2
      DO 306 J=2,M2
COEFFICIENTS AEAST AND AWEST
      FL=ZCVK(K)*U(2,J,K)*RHO(1,J,K)
      FLM=ZCVKP(K-1)*U(2,J,K-1)*RHO(1,J,K-1)
      FLOW=YCV(J)*(FL+FLM)
      GM=ZCVK(K)*GAM(1,J,K)+ZCVKP(K-1)*GAM(1,J,K-1)
      DIFF=YCV(J)*GM/XDIF(2)
```

```
      CALL PROFIL
      AIM(2,J,K)=ACOF+AMAX1(ZERO,FLOW)
      FL=ZCVK(K)*U(L1,J,K)*RHO(L1,J,K)
      FLM=ZCVKP(K-1)*U(L1,J,K-1)*RHO(L1,J,K-1)
      FLOW=YCV(J)*(FL+FLM)
      GM=ZCVK(K)*GAM(L1,J,K)+ZCVKP(K-1)*GAM(L1,J,K-1)
      DIFF=YCV(J)*GM/XDIF(L1)
      CALL PROFIL
      AIP(L2,J,K)=ACOF+AMAX1(ZERO,FLOW)-FLOW
306   CONTINUE
C     WRITE(*,*) ' W: COEFF 5'
      DO 307 I=2,L2
      DO 307 J=2,M2
      DO 307 K=3,N2
      VOL=YCV(J)*ZCVS(K)*XCV(I)
      APT=(RHO(I,J,K)*ZCVK(K)+RHO(I,J,K-1)*ZCVKP(K-1))
     1/(ZCVS(K)*DT)
      AP(I,J,K)=AP(I,J,K)-APT
      CON(I,J,K)=CON(I,J,K)+APT*W0(I,J,K)
      AP(I,J,K)=
     1 (-AP(I,J,K)*VOL+AIP(I,J,K)+AIM(I,J,K)+AJP(I,J,K)+AJM(I,J,K)
     2 +AKP(I,J,K)+AKM(I,J,K))
     3/RELAX(NF)
*********************************************************source term
*****************************************************************
      CON(I,J,K)=CON(I,J,K)*VOL+REL*AP(I,J,K)*W(I,J,K)
      DW(I,J,K)=VOL/ZDIF(K)
      DW(I,J,K)=DW(I,J,K)/AP(I,J,K)
 307  CONTINUE
      IF(ICALL.EQ.1) THEN
      DO 9099 I=2,L2
      DO 9099 J=2,M2
      DO 9099 K=3,N2
9099  WHAT(I,J,K)=(AIP(I,J,K)*W(I+1,J,K)+AIM(I,J,K)*W(I-1,J,K)
     1      +AJP(I,J,K)*W(I,J+1,K)+AJM(I,J,K)*W(I,J-1,K)
     2      +AKP(I,J,K)*W(I,J,K+1)+AKM(I,J,K)*W(I,J,K-1)
     3      +CON(I,J,K))/AP(I,J,K)
      ENDIF
 300  CONTINUE
      RETURN
      end
C
C ***********************************************************************
      subroutine PCOF
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
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 5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
 6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
 7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
 8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
  COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
 1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
 2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
  COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
 1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
 2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
 3IST,JST,KST,ITER,LAST,
 4IPREF,JPREF,KPREF,MODE
  COMMON/HEADIN/TITLE
  CHARACTER*10 TITLE(13)
  COMMON/CNTL/LSTOP,ICALL,ISTOP
  COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
 1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
  COMMON/RESID/RMAX(13),IRESID
  COMMON/SORC/SMAX,SSUM
  COMMON/COEF/FLOW,DIFF,ACOF
  common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
  DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
  DIMENSION T(35,25,35)
  EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
 1       (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
 2       ,(F(1,1,1,5),T(1,1,1))
C
COEFFICIENTS FOR THE PRESSURE EQUATION__________________
C
  NF=NP
  IST=2
  JST=2
  KST=2
c   WRITE(*,*) ' PC: COEFF 1'
  DO 501 J=2,M2
  DO 501 K=2,N2
   AIM(2,J,K)=0.0
   AIP(L2,J,K)=0.0
   CON(2,J,K)=RHO(1,J,K)*U(2,J,K)*YCV(J)*ZCV(K)
   CON(L1,J,K)=0.
 501 CONTINUE
  DO 502 I=2,L2
  DO 502 K=2,N2
   AJM(I,2,K)=0.0
   AJP(I,M2,K)=0.0
   CON(I,2,K)=RHO(I,1,K)*V(I,2,K)*XCV(I)*ZCV(K)
   CON(I,M1,K)=0.
 502 CONTINUE
  DO 503 I=2,L2
  DO 503 J=2,M2
   AKM(I,J,2)=0.0
```

```
      AKP(I,J,N2)=0.0
      CON(I,J,2)=RHO(I,J,1)*W(I,J,2)*XCV(I)*YCV(J)
 503  CONTINUE
C
C     WRITE(*,*) ' PC: COEFF 2'
      DO 504 K=2,N2
      DO 504 J=2,M2
      DO 504 I=2,L2
      AREA=YCV(J)*ZCV(K)
      ARHO=AREA*(FX(I+1)*RHO(I+1,J,K)+FXM(I+1)*RHO(I,J,K))
      FLOW=ARHO*PC(I+1,J,K)
      IF(I.EQ.L2) FLOW=ARHO*U(L1,J,K)
      IF(ABS(FLOW).LT.1E-20) FLOW=0.
      AIP(I,J,K)=ARHO*DU(I+1,J,K)
      AIM(I+1,J,K)=AIP(I,J,K)
      CON(I,J,K)=CON(I,J,K)-FLOW
      CON(I+1,J,K)=CON(I+1,J,K)+FLOW
C
      AREA=XCV(I)*ZCV(K)
      ARHO=AREA*(FY(J+1)*RHO(I,J+1,K)+FYM(J+1)*RHO(I,J,K))
      FLOW=ARHO*VHAT(I,J+1,K)
      IF(J.EQ.M2)FLOW=ARHO*V(I,M1,K)
      IF(ABS(FLOW).LT.1E-20) FLOW=0.
      AJP(I,J,K)=ARHO*DV(I,J+1,K)
      AJM(I,J+1,K)=AJP(I,J,K)
      CON(I,J,K)=CON(I,J,K)-FLOW
      CON(I,J+1,K)=CON(I,J+1,K)+FLOW
      AREA=XCV(I)*YCV(J)
      ARHO=AREA*(FZ(K+1)*RHO(I,J,K+1)+FZM(K+1)*RHO(I,J,K))
      FLOW=ARHO*WHAT(I,J,K+1)
      IF(K.EQ.N2)FLOW=ARHO*W(I,J,N1)
      AKP(I,J,K)=ARHO*DW(I,J,K+1)
      AKM(I,J,K+1)=AKP(I,J,K)
      IF(ABS(FLOW).LT.1E-20) FLOW=0.
      CON(I,J,K)=CON(I,J,K)-FLOW
      CON(I,J,K+1)=FLOW
C     WRITE(*,*) ' 3',I,J,K
      AP(I,J,K)=AIP(I,J,K)+AIM(I,J,K)+AJP(I,J,K)+AJM(I,J,K)
     1      +AKP(I,J,K)+AKM(I,J,K)
 504  CONTINUE
      RETURN
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE umesh
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
       COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
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4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
 COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
 COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
3IST,JST,KST,ITER,LAST,
4IPREF,JPREF,KPREF,MODE
 COMMON/HEADIN/TITLE
 CHARACTER*10 TITLE(13)
 COMMON/CNTL/LSTOP,ICALL,ISTOP
 COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
 COMMON/SORC/SMAX,SSUM
 COMMON/COEF/FLOW,DIFF,ACOF
 DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
 common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
 DIMENSION T(35,25,35)
 EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
1       (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
2       ,(F(1,1,1,5),T(1,1,1))
C------------------------------------------
 10 FORMAT(26(1H*),3X,A10,3X,26(1H*))
 20 FORMAT(1X,4H I =,I6,6I9)
 30 FORMAT(1X,1HJ)
 40 FORMAT(1X,I2,3X,1P,7E9.2)
 50 FORMAT(1H )
 51 FORMAT(1X,'I =',2X,7(I4,5X))
 52 FORMAT(1X,'X =',1P,7E9.2)
 53 FORMAT('TH =',1P,7E9.2)
 54 FORMAT(1X,'J =',2X,7(I4,5X))
 55 FORMAT(1X,'Y =',1P,7E9.2)
 56 FORMAT(1X,'K =',2X,7(I4,5X))
 57 FORMAT(1X,'Z =',1P,7E9.2)
 59 FORMAT(1X,'K =',2X,I4)
C*************************************************
c  ENTRY UMESH
C*************************************************
   XU(2)=0.
   DX=XL/FLOAT(L1-2)
   DO 1 I=3,L1
 1 XU(I)=XU(I-1)+DX
   YV(2)=0.
   DY=YL/FLOAT(M1-2)
   DO 2 J=3,M1
 2 YV(J)=YV(J-1)+DY
```

```
      ZW(2)=0.
      DZ=ZL/FLOAT(N1-2)
      DO 3 K=3,N1
    3 ZW(K)=ZW(K-1)+DZ
      RETURN
      end
C**************************************************
      subroutine PRINT
C**************************************************
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
      COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
     6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
     7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
     8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
      COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
     1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
     2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
      COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
     1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
     2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
     3IST,JST,KST,ITER,LAST,
     4IPREF,JPREF,KPREF,MODE
      COMMON/HEADIN/TITLE
      CHARACTER*10 TITLE(13)
      COMMON/CNTL/LSTOP,ICALL,ISTOP
      COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
     1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
      COMMON/SORC/SMAX,SSUM
      COMMON/COEF/FLOW,DIFF,ACOF
      DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
      common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
      DIMENSION T(35,25,35)
      EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
     1      (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
     2      ,(F(1,1,1,5),T(1,1,1))
C-----------------------------------------------------
   10 FORMAT(26(1H*),3X,A10,3X,26(1H*))
   20 FORMAT(1X,4H I =,I6,6I9)
   30 FORMAT(1X,1HJ)
   40 FORMAT(1X,I2,3X,1P,7E9.2)
   50 FORMAT(1H )
   51 FORMAT(1X,'I =',2X,7(I4,5X))
   52 FORMAT(1X,'X =',1P,7E9.2)
   53 FORMAT('TH =',1P,7E9.2)
   54 FORMAT(1X,'J =',2X,7(I4,5X))
```

```
 55 FORMAT(1X,'Y =',1P,7E9.2)
 56 FORMAT(1X,'K =',2X,7(I4,5X))
 57 FORMAT(1X,'Z =',1P,7E9.2)
 59 FORMAT(1X,'K =',2X,I4)

   IF(.NOT.LPRINT(3)) GO TO 80
 80 CONTINUE
C
   IF(.NOT.LPRINT(NP)) GO TO 90
C
CONSTRUCT BOUNDARY PRESSURES BY EXTRAPOLATION
C
   DO 91 K=2,N2
   DO 91 J=2,M2
   P(1,J,K)=(P(2,J,K)*XCVS(3)-P(3,J,K)*XDIF(2))/XDIF(3)
 91 P(L1,J,K)=(P(L2,J,K)*XCVS(L2)-P(L3,J,K)*XDIF(L1))/XDIF(L2)
   DO 92 K=2,N2
   DO 92 I=2,L2
   P(I,1,K)=(P(I,2,K)*YCVS(3)-P(I,3,K)*YDIF(2))/YDIF(3)
 92 P(I,M1,K)=(P(I,M2,K)*YCVS(M2)-P(I,M3,K)*YDIF(M1))/YDIF(M2)
   DO 93 J=2,M2
   DO 93 I=2,L2
   P(I,J,1)=(P(I,J,2)*ZCVS(3)-P(I,J,3)*ZDIF(2))/ZDIF(3)
 93 P(I,J,N1)=(P(I,J,N2)*ZCVS(N2)-P(I,J,N3)*ZDIF(N1))/ZDIF(N2)
   DO 94 K=2,N2
   P(1,1,K)=P(2,1,K)+P(1,2,K)-P(2,2,K)
 94 CONTINUE
   DO 95 J=2,M2
   P(1,J,1)=P(2,J,1)+P(1,J,2)-P(2,J,2)
 95 CONTINUE
   DO 96 I=2,L2
   P(I,1,1)=P(I,2,1)+P(I,1,2)-P(I,2,2)
 96 CONTINUE
   P(1,1,1)=(P(1,1,2)+P(1,2,1)+P(2,1,1))/3.0
   P(L1,1,1)=(P(L2,1,1)+P(L1,2,1)+P(L1,1,2))/3.0
   P(1,1,N1)=(P(1,1,N2)+P(1,2,N1)+P(2,1,N1))/3.0
   P(1,M1,1)=(P(1,M2,1)+P(1,M1,2)+P(2,M1,1))/3.0
   P(L1,M1,1)=(P(L2,M1,1)+P(L1,M2,1)+P(L1,M1,2))/3.0
   P(1,M1,N1)=(P(2,M1,N1)+P(1,M2,N1)+P(1,M1,N2))/3.0
   P(L1,M1,N1)=(P(L2,M1,N1)+P(L1,M2,N1)+P(L1,M1,N2))/3.0
   PREF=P(IPREF,JPREF,KPREF)
   DO 97 K=1,N1
   DO 97 J=1,M1
   DO 97 I=1,L1
 97 P(I,J,K)=P(I,J,K)-PREF
 90 CONTINUE
C
c  PRINT 50
   write(16,50)
   IEND=0
 301 IF(IEND.EQ.L1) GO TO 310
```

```
      IBEG=IEND+1
      IEND=IEND+7
      IEND=MIN0(IEND,L1)
c     PRINT 50
      write(16,50)
c     PRINT 51,(I,I=IBEG,IEND)
      write(16,51)(i,i=ibeg,iend)
      IF(MODE.EQ.3) GO TO 302
c     PRINT 52,(X(I),I=IBEG,IEND)
      write(16,52)(x(i),i=ibeg,iend)
      GO TO 303
c 302 PRINT 53,(X(I),I=IBEG,IEND)
  302 write(16,53)(x(i),i=ibeg,iend)
  303 GO TO 301
  310 JEND=0
c     PRINT 50
      write(16,50)
  311 IF(JEND.EQ.M1) GO TO 320
      JBEG=JEND+1
      JEND=JEND+7
      JEND=MIN0(JEND,M1)
c     PRINT 50
      write(16,50)
c     PRINT 54,(J,J=JBEG,JEND)
      write(16,54)(j,j=jbeg,jend)
c     PRINT 55,(Y(J),J=JBEG,JEND)
      write(16,55)(y(j),j=jbeg,jend)
      GO TO 311
  320 KEND=0
c     PRINT 50
      write(16,50)
  321 IF(KEND.EQ.N1) GO TO 330
      KBEG=KEND+1
      KEND=KEND+7
      KEND=MIN0(KEND,N1)
c     PRINT 50
      write(16,50)
c     PRINT 56,(K,K=KBEG,KEND)
      write(16,56)(k,k=kbeg,kend)
c     PRINT 57,(Z(K),K=KBEG,KEND)
      write(16,57)(z(k),k=kbeg,kend)
      GO TO 321
  330 CONTINUE
C
      DO 999 NF=1,NGAM
c     do 999 nf=5,5
      IF(.NOT.LPRINT(NF)) GO TO 999
c     PRINT 50
      write(16,50)
c     PRINT 10,TITLE(NF)
      write(16,10)title(nf)
```

```
      DO 998 K=1,N1
c     PRINT 50
      write(16,50)
c     PRINT 59,K
      write(16,59)k
      IFST=1
      JFST=1
      KFST=1
      IF(NF.EQ.1.OR.NF.EQ.4) IFST=2
      IF(NF.EQ.2.OR.NF.EQ.4) JFST=2
      IF(NF.EQ.3.OR.NF.EQ.4) KFST=2
      IBEG=IFST-7
  110 CONTINUE
      IBEG=IBEG+7
      IEND=IBEG+6
      IEND=MIN0(IEND,L1)
c     PRINT 50
      write(16,50)
c     PRINT 20,(I,I=IBEG,IEND)
      write(16,20)(i,i=ibeg,iend)
c     PRINT 30
      write(16,30)
      JFL=JFST+M1
      DO 115 JJ=JFST,M1
      J=JFL-JJ
c     PRINT 40,J,(F(I,J,K,NF),I=IBEG,IEND)
      write(16,40)j,(f(i,j,k,nf),i=ibeg,iend)
  115 CONTINUE
      IF(IEND.LT.L1) GO TO 110
  998 CONTINUE
  999 CONTINUE
      RETURN
      END
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C              PROBLEM DEPENDENT PORTION                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      BLOCK DATA
C*********************************************************
c      LOGICAL LSTOP
c      INTEGER*4 NOW(14)
c      COMMON/CNTL/LSTOP,ICALL,ISTOP
      LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
      COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
     1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
     2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
       COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
     3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
     4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
     5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
```

```
 6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
 7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
 8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
  COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
 1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
 2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
  COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
 1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
 2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
 3IST,JST,KST,ITER,LAST,
 4IPREF,JPREF,KPREF,MODE
  COMMON/HEADIN/TITLE
  CHARACTER*10 TITLE(13)
  COMMON/CNTL/LSTOP,ICALL,ISTOP
  COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
 1    U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
  COMMON/RESID/RMAX(13),IRESID
  COMMON/SORC/SMAX,SSUM
  common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
  COMMON/COEF/FLOW,DIFF,ACOF
  DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
  DIMENSION T(35,25,35)
  EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
 1      (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
 2     ,(F(1,1,1,5),T(1,1,1))

  DATA NFMAX,NP,NRHO,NGAM/5,6,7,8/
  DATA LSTOP,LSOLVE,LPRINT/24*.FALSE./
  DATA MODE,TIME,ITER,IRESID,ITER1/1,0.,0,0,1/
  DATA RELAX,NTIMES/13*.3,10*5/
  DATA LBLK/11*.TRUE./
  DATA DT,IPREF,JPREF,KPREF,RHOCON/1.E+10,1,1,1,1.0/
C*******************************************************************
C NF=1,2,3 STAND FOR U,V AND W VELOCITIES.
C NF=4 IS FOR PRESSURE
C NF=5 IS FOR TEMPERATURE
C LSOLVE=TRUE SOLVES THAT PARTICULAR PHI
   DATA (LSOLVE(I),I=1,6)/6*.TRUE./
C   DATA (LSOLVE(I),I=1,6)/4*.FALSE.,.TRUE.,.FALSE./
C LPRINT(NF)=TRUE PRINTS VARIABLE ASSOCIATED WITH NF ON CALLING PRINT
C   DATA LPRINT(1), LPRINT(5)/2*.TRUE./
C TERMINATE ITERATIONS AT ITER=LAST
   DATA LAST/100/
C UNDERELAXATION FACTORS
c   DATA RELAX(1),RELAX(2),RELAX(3),RELAX(4)/0.7,0.7,0.7,.7/
c   DATA RELAX(5),RELAX(6)/.7,.7/
C TITLES FOR THE FIELD PRINTOUTS
   DATA TITLE(1),TITLE(2),TITLE(3),TITLE(5),TITLE(6)/
   1'U','V','W','T','P'/
C NUMBER OF SWEEPS IN THE LINE-BY-LINE TDMA ALGORITHM
c   DATA NTIMES(4),NTIMES(5)/2*2/
```

```
C TOLERANCES FOR CONVERGENCE
   DATA EPSU,EPSV,EPSW,EPST/1.0E-3,1.0E-3,1.0E-3,5.0E-2/
   DATA ZERO/0./
   END
C***************************************************************
C***************************************************************
   SUBROUTINE USE
C***************************************************************
C IF LARGER NUMBER OF GRID POINTS IS TO BE USED, THE DIMENSION
C STATEMENTS MUST BE CHANGED THROUGH THE PROGRAM TO ACCOMODATE
C VALUES GRAETER THAN (28,26,28) ETC.
C************************************************************
c   LOGICAL LSTOP
c   INTEGER*4 NOW(14)
c   COMMON/CNTL/LSTOP,ICALL,ISTOP
   LOGICAL LSOLVE,LPRINT,LBLK,LSTOP
   COMMON F(35,25,35,5),P(35,25,35),RHO(35,25,35),GAM(35,25,35),
  1 CON(35,25,35),AKP(35,25,35),AKM(35,25,35),AP(35,25,35),
  2 AIP(35,25,35),AIM(35,25,35),AJP(35,25,35),AJM(35,25,35)
   COMMON delh(35,25,35),delh0(35,25,35),epsi(35,25,35),
  3 X(35),XU(35),XDIF(35),XCV(35),XCVS(35),tk,cp,alatent,
  4 Y(35),YV(35),YDIF(35),YCV(35),YCVS(35),tmelt,tprev(35,25,35),
  5 Z(35),ZW(35),ZDIF(35),ZCV(35),ZCVS(35),ap0(35,25,35),
  6 YCVR(35),YCVRS(35),ARX(35),ARXJ(35),ARXJP(35),ap1(35,25,35),
  7 R(35),RMN(35),SX(35),SXMN(35),XCVI(35),XCVIP(35),
  8 YCVJ(35),YCVJP(35),ZCVK(35),ZCVKP(35),st(35,25,35)
   COMMON DU(35,25,35),DV(35,25,35),DW(35,25,35),FV(35),FVP(35),
  1 FX(35),FXM(35),FY(35),FYM(35),PT(35),QT(35),TOLD(35,25,35),
  2 FZ(35),FZM(35),VHAT(35,25,35),WHAT(35,25,35),UOLD(35,25,35)
   COMMON/INDX/RELAX(13),LPRINT(13),LBLK(11),NTIMES(10),
  1LSOLVE(10),TIME,DT,XL,YL,ZL,S,RHOCON,ZERO,TLAST,
  2NF,NFMAX,NP,NRHO,NGAM,L1,L2,L3,M1,M2,M3,N1,N2,N3,
  3IST,JST,KST,ITER,LAST,
  4IPREF,JPREF,KPREF,MODE
   COMMON/HEADIN/TITLE
   CHARACTER*10 TITLE(13)
   COMMON/CNTL/LSTOP,ICALL,ISTOP
   COMMON/CONV1/EPSU,EPSV,EPSW,EPST,ICONV,ITER1,T0(35,25,35),ENBAL,
  1   U0(35,25,35),V0(35,25,35),W0(35,25,35),ITERL
   COMMON/RESID/RMAX(13),IRESID
   COMMON/SORC/SMAX,SSUM
   common/force/xforce(35,25,35),yforce(35,25,35),zforce(35,25,35)
   COMMON/COEF/FLOW,DIFF,ACOF
   DIMENSION U(35,25,35),V(35,25,35),W(35,25,35),PC(35,25,35)
   DIMENSION T(35,25,35),imat(35,25,35),xu1(35), yv1(35),zw1(35)
   EQUIVALENCE(F(1,1,1,1),U(1,1,1)),(F(1,1,1,2),V(1,1,1)),
  1      (F(1,1,1,3),W(1,1,1)),(F(1,1,1,4),PC(1,1,1))
  2      ,(F(1,1,1,5),T(1,1,1))
   DIMENSION PRTTM(10)
   DATA IPR,RRTOL,IIPR/1,0.38E-5,1/C************************************************
   ENTRY MESH
```

```
C
C DOMAIN LENGHTS IN THE 3 DIRECTIONS
  XL=5.1
  YL=5.04
  ZL=5.04
C NUMBER OF GRID POINTS IN THE 3 DIRECTIONS
  L1=28
  M1=24
  N1=24
C
  XU(2)=0.
  XU(3)=0.08
  XU(4)=0.085
  XU(5)=0.100
  XU(6)=0.1274
  XU(7)=0.131
  XU(8)=0.174
  XU(9)=0.259
  XU(10)=0.29
  XU(11)=0.30
  XU(12)=0.33
  XU(13)=0.36
  XU(14)=0.50
  XU(15)=0.65
  XU(16)=0.8
  XU(17)=1.00
  XU(18)=1.75
  XU(19)=2.5
  XU(20)=3.25
  XU(21)=4.0
  XU(22)=4.5
  XU(23)=4.75
  XU(24)=4.85
  XU(25)=4.95
  XU(26)=5.03
  XU(27)=5.07
  XU(28)=5.10
C
  ZW(2)=0.
  ZW(3)=0.48
  ZW(4)=0.58
  ZW(5)=0.885
  ZW(6)=0.94
  ZW(7)=0.995
  ZW(8)=1.296
  ZW(9)=1.396
  ZW(10)=2.106
  ZW(11)=2.206
  ZW(12)=2.511
  ZW(13)=2.566
  ZW(14)=2.621
```

```
      ZW(15)=2.926
      ZW(16)=3.026
      ZW(17)=3.736
      ZW(18)=3.836
      ZW(19)=4.141
      ZW(20)=4.196
      ZW(21)=4.251
      ZW(22)=4.561
      ZW(23)=4.661
      ZW(24)=5.04
C
      YV(2)=0.
      YV(3)=0.48
      YV(4)=0.58
      YV(5)=0.885
      YV(6)=0.94
      YV(7)=0.995
      YV(8)=1.296
      YV(9)=1.396
      YV(10)=2.106
      YV(11)=2.206
      YV(12)=2.511
      YV(13)=2.566
      YV(14)=2.621
      YV(15)=2.926
      YV(16)=3.026
      YV(17)=3.736
      YV(18)=3.836
      YV(19)=4.141
      YV(20)=4.196
      YV(21)=4.251
      YV(22)=4.561
      YV(23)=4.661
      YV(24)=5.04
C
      ENTRY BEGIN
C INITIAL TIME
c     WRITE(*,*)' INITIAL TIME'
       TIME=0.0
C INITIAL TIME STEP
c     WRITE(*,*)'INITIAL TIME STEP'
       DT=30.
C ITERATIONS STOP AT ITER=LAST
c     WRITE(*,*)'FINISH TIME'
      TLAST=1000.0
C     HOW MANY TIMES SHOULD FULL DATA BE PRINTED TO FILE
c     WRITE(*,*) ' NUMBER OF TIMES FOR PRINTING DATA TO FILE'
      NNPR=2
C     WHEN IS DATA TO BE PRINTED
c     WRITE(*,*) ' PRTTM1,PRTTM2,...'
       PRTTM(1)=0.0
```

```
      PRTTM(2)=500.0
c     PRTTM(3)=100.0

C READ RAYLEIGH NUMBER
c     WRITE(*,*)'RALI='
      RA=1.15e3
C READ PRNDTL NUMBER
c     WRITE(*,*)'PRANTL='
      PR=24
C READ XLHC RATIO
c     WRITE(*,*)'CHIP HEIGHT TO PACKAGE LENGTH RATIO'
      XLHC=0.043
c     WRITE(*,*)'CHIP LENGTH TO PACKAGE LENGTH RATIO'
      XLLC=0.017
C READ RATIO OF CONDUCTIVITIES
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (CHIP-TO-FLUID)'
      RC=2360.0
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (SUBSTRATE-TO-FLUID)'
      RS=333.0
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (PACKAGE-TO-FLUID)'
      RP=266.0
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (LID-TO-FLUID)'
      RL=271.0
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (AIR-TO-FLUID)'
      RR=0.42
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (SOLDER-TO-FLUID)'
      RG=796.0
c     WRITE(*,*)'RATIO OF CONDUCTIVITIES (GOLD COATING-TO-FLUID)'
      RM=3900.0
C READ RATIO OF THERMAL INERTIA
c     WRITE(*,*)'RATIO OF RHO*CP (SUBSTRATE-TO-FLUID)'
      RHOCS=1.63
c     WRITE(*,*)'RATIO OF RHOC*CP (CHIP-TO-FLUID)'
      RHOCC=0.9
c     WRITE(*,*)'RATIO OF RHO*CP (PACKAGE-TO-FLUID)'
      RHOCP=1.68
c     WRITE(*,*)'RATIO OF RHO*CP (LID-TO-FLUID)'
      RHOCL=1.98
c     WRITE(*,*)'RATIO OF RHO*CP (AIR-TO-FLUID)'
      RHOCR=0.00064
c     WRITE(*,*)'RATIO OF RHO*CP (SOLDER-TO-FLUID)'
      RHOCG=0.68
c     WRITE(*,*)'RATIO OF RHO*CP (GOLD-TO-FLUID)'
      RHOCM=1.36
C READ WHETHER TO RAMP SOURCE TERMS
c     WRITE(*,*)'RAMP SOURCE TERMS (0/1)'
      IRAMP=1
C DETERMINE IF WANT TO USE A PREVIOUSLY COMPUTED SOLUTION AS
C AN INITIAL GUESS
c     WRITE(*,*)'READ FROM INPUT FILE (0/1)'
      IREAD=1
```

```
      IF(IREAD.EQ.1)LREAD=.TRUE.
      IF(IREAD.EQ.0)LREAD=.FALSE.
C READ IN RELAXATION PARAMETERS
c     WRITE(*,*) ' ENTER relaxation'
      RELAX(1)=0.4
      RELAX(2)=0.4
      RELAX(3)=0.4
      RELAX(4)=0.4
      RELAX(5)=0.4
      RELAX(6)=0.4
C PROVIDE INITIAL GUESS. THE PROGRAM SOLVES FOR THE INTERIOR POINTS
C ONLY.  HENCE THE BOUNDARY VALUSE FOR THE TEMPERATURES AT THE HOT
C AND COLD BOUNDARIES HAVE BEEN ALREADY SPECIFIED.
C***************************
      DO 100 I=1,L1
      DO 100 J=1,M1
      DO 100 K=1,N1
IMAT(I,J,K)=0
RHO(I,J,K)=1.0
 100  CONTINUE
      DO 101 I=1,L1
      DO 101 J=1,M1
      DO 101 K=1,N1
      U(I,J,K)=0.
      V(I,J,K)=0.
      W(I,J,K)=0.
      T(I,J,K)=0.
      IF(I.NE.L1) T(I,J,K)= 0.075
C  SET UP MATERIAL TYPE ARRAY
C  SUBSRATE
      IF(I.LE.2) THEN
IMAT(I,J,K)=-1
RHO(I,J,K)=RHOCS
      ENDIF
C COMPONENT DETAILS
      IF (I.LE.8.AND.I.GE.4.AND.
     1      (J.GE.4.AND.J.LE.9.OR.J.GE.11.AND.J.LE.16.
     2  OR.J.GE.18.AND.J.LE.23).AND.(
     3      K.GE.4.AND. K.LE.9.OR.K.GE.11.AND.K.LE.16.
     4   OR.K.GE.18.AND.J.LE.23)) THEN
C CHIP AND AIR GAP
 IF (I.EQ.7) THEN
IF(
     1      (J.GE.4.AND.J.LE.9.OR.J.GE.11.AND.J.LE.16.
     2  OR.J.GE.18.AND.J.LE.23).AND.(
     3      K.GE.4.AND. K.LE.9.OR.K.GE.11.AND.K.LE.16.
     4   OR.K.GE.18.AND.J.LE.23)) THEN

IMAT(I,J,K)=3

RHO(I,J,K)=RHOCR
```

```
 ENDIF
C CHIP
   IF(
 1      (J.GE.6.AND.J.LE.7.OR.J.GE.13.AND.J.LE.14.
 2  OR.J.GE.20.AND.J.LE.21).AND.(
 3      K.GE.6.AND. K.LE.7.OR.K.GE.13.AND.K.LE.14.
 4   OR.K.GE.20.AND.J.LE.21)) THEN
   IMAT(I,J,K)=1
   RHO(I,J,K)=RHOCC
   ENDIF
        ENDIF
c  AIR SPACE ABOVE CHIP
 IF (I.EQ.8) THEN
    IF(
 1      (J.GE.4.AND.J.LE.9.OR.J.GE.11.AND.J.LE.16.
 2  OR.J.GE.18.AND.J.LE.23).AND.(
 3      K.GE.4.AND. K.LE.9.OR.K.GE.11.AND.K.LE.16.
 4   OR.K.GE.18.AND.J.LE.23)) THEN
  IMAT(I,J,K)=3
   RHO(I,J,K)=RHOCR
 ENDIF
ENDIF
C  GOLD/TUNGSTEN COATING BELOW DIE (CHIP)
 IF(I.EQ.6) THEN
   IF(
 1      (J.GE.4.AND.J.LE.9.OR.J.GE.11.AND.J.LE.16.
 2  OR.J.GE.18.AND.J.LE.23).AND.(
 3      K.GE.4.AND. K.LE.9.OR.K.GE.11.AND.K.LE.16.
 4   OR.K.GE.18.AND.J.LE.23)) THEN
    IMAT(I,J,K)=7
   RHO(I,J,K)=RHOCM
 ENDIF
ENDIF
C  PACKAGE
 IF(IMAT(I,J,K).EQ.0) THEN
   IMAT(I,J,K)=2
   RHO(I,J,K)=RHOCP
   ENDIF
   ENDIF
C  LID
   IF (I.EQ.9) THEN
     IF(
 1      (J.GE.4.AND.J.LE.9.OR.J.GE.11.AND.J.LE.16.
 2  OR.J.GE.18.AND.J.LE.23).AND.(
 3      K.GE.4.AND. K.LE.9.OR.K.GE.11.AND.K.LE.16.
 4   OR.K.GE.18.AND.J.LE.23)) THEN
   IMAT(I,J,K)=4
   RHO(I,J,K)=RHOCL
    ENDIF
   ENDIF
C  FLUID BEWTEEN CHIP AND SUBSTRATE
```

```
IF (I.EQ.3)THEN
  IF(
1      J.GE.4.AND.J.LE.9.OR.J.GE.11.AND.J.LE.16.
2  OR.J.GE.18.AND.J.LE.23.AND.
3      K.GE.4.AND. K.LE.9.OR.K.GE.11.AND.K.LE.16.
4   OR.K.GE.18.AND.J.LE.23) THEN
IMAT(I,J,K)=6
RHO(I,J,K)=1.0
   ENDIF
ENDIF
c SOLDER CONNECTION BEWTEEN CHIP AND SUBSTRATE
     IF (I.EQ.3)then
      IF(J.EQ.4.AND.
2     (K.EQ.5.OR.K.EQ.8.OR.K.EQ.12.OR.K.EQ.15.
2     OR.K.EQ.19.OR.K.EQ.22))then
    IMAT(I,J,K)=5
   RHO(I,J,K)=RHOCG
   ENDIF
      IF(J.EQ.9.AND.
2     (K.EQ.5.OR.K.EQ.8.OR.K.EQ.12.OR.K.EQ.15.
2     OR.K.EQ.19.OR.K.EQ.22))THEN
       IMAT(I,J,K)=5
      RHO(I,J,K)=RHOCG
      ENDIF
      IF(J.EQ.11.AND.
2     (K.EQ.5.OR.K.EQ.8.OR.K.EQ.12.OR.K.EQ.15.
2     OR.K.EQ.19.OR.K.EQ.22))THEN
       IMAT(I,J,K)=5
      RHO(I,J,K)=RHOCG
       ENDIF
      IF(J.EQ.16.AND.
2     (K.EQ.5.OR.K.EQ.8.OR.K.EQ.12.OR.K.EQ.15.
2     OR.K.EQ.19.OR.K.EQ.22))THEN
        IMAT(I,J,K)=5
       RHO(I,J,K)=RHOCG
        ENDIF
       IF(J.EQ.18.AND.
2     (K.EQ.5.OR.K.EQ.8.OR.K.EQ.12.OR.K.EQ.15.
2     OR.K.EQ.19.OR.K.EQ.22))THEN
        IMAT(I,J,K)=5
       RHO(I,J,K)=RHOCG
       ENDIF
      IF(J.EQ.23.AND.
2     (K.EQ.5.OR.K.EQ.8.OR.K.EQ.12.OR.K.EQ.15.
2     OR.K.EQ.19.OR.K.EQ.22))THEN
        IMAT(I,J,K)=5
        RHO(I,J,K)=RHOCG
       ENDIF
      IF(J.EQ.5.AND.
2     (K.EQ.4.OR.K.EQ.9.OR.K.EQ.11.OR.K.EQ.16.
2     OR.K.EQ.18.OR.K.EQ.23))THEN
```

```
         IMAT(I,J,K)=5
         RHO(I,J,K)=RHOCG
         ENDIF
        IF(J.EQ.8.AND.
     2   (K.EQ.4.OR.K.EQ.9.OR.K.EQ.11.OR.K.EQ.16.
     2   OR.K.EQ.18.OR.K.EQ.23))THEN
          IMAT(I,J,K)=5
          RHO(I,J,K)=RHOCG
         ENDIF
        IF(J.EQ.12.AND.
     2   (K.EQ.4.OR.K.EQ.9.OR.K.EQ.11.OR.K.EQ.16.
     2   OR.K.EQ.18.OR.K.EQ.23))THEN
          IMAT(I,J,K)=5
          RHO(I,J,K)=RHOCG
          ENDIF
        IF(J.EQ.15.AND.
     2   (K.EQ.4.OR.K.EQ.9.OR.K.EQ.11.OR.K.EQ.16.
     2   OR.K.EQ.18.OR.K.EQ.23))THEN
          IMAT(I,J,K)=5
          RHO(I,J,K)=RHOCG
         ENDIF
        IF(J.EQ.19.AND.
     2   (K.EQ.4.OR.K.EQ.9.OR.K.EQ.11.OR.K.EQ.16.
     2   OR.K.EQ.18.OR.K.EQ.23))THEN
          IMAT(I,J,K)=5
          RHO(I,J,K)=RHOCG
           ENDIF
        IF(J.EQ.22.AND.
     2   (K.EQ.4.OR.K.EQ.9.OR.K.EQ.11.OR.K.EQ.16.
     2   OR.K.EQ.18.OR.K.EQ.23))THEN
          IMAT(I,J,K)=5
         RHO(I,J,K)=RHOCG
       ENDIF
      ENDIF
101 CONTINUE
      do 576 i=1,l1
      do 576 j=1,m1
      do 576 k=1,n1
      write(20,*) i,j,k,rho(i,j,k)
576 continue

      IF(.NOT.LREAD) RETURN
C READ DATA FROM INPUT FILE
      REWIND (7)
      READ(7,*) X,Y,Z,XU1,YV1,ZW1,U,V,W,P,T
      ICHK=0
      DO 102 I=2,L1
      IF(ABS(XU1(I)-XU(I)).GT.1E-7) THEN
 ICHK=1
 WRITE(*,*) 'I,XU(I),XU1(I)',I,XU(I),XU1(I)
      ENDIF
```

```
 102 CONTINUE
   DO 103 J=2,M1
    IF(ABS(YV1(J)-YV(J)).GT.1E-7) THEN
ICHK=1
WRITE(*,*) 'J,YV(J),YV1(J)',J,YV(J),YV1(J)
    ENDIF
 103 CONTINUE
   DO 104 K=2,N1
    IF(ABS(ZW1(K)-YV(K)).GT.1E-7) THEN
ICHK=1
WRITE(*,*) 'K,YV(K),ZW1(K)',K,YV(K),ZW1(K)
    ENDIF
 104 CONTINUE
   IF(ICHK.EQ.1) STOP
   RETURN
C
C************************************************
   ENTRY VARRHO
C************************************************
   RETURN
C
C************************************************
C INCORPORATE BOUNDARY CONDITIONS
   ENTRY BNDRY
   DO 864 I=1,L1
   DO 864 J=1,M1
C ADIABATIC SIDES (Z=0,Z=1)
   T(I,J,1)=T(I,J,2)
   T(I,J,N1)=T(I,J,N2)
 864 CONTINUE
   DO 865 J=1,M1
   DO 865 K=1,N1
C ADIABATIC SIDE (X=0)
   T(1,J,K)=T(2,J,K)
   T(L1,J,K)=0.
 865 CONTINUE
   DO 866 I=1,L1
   DO 866 K=1,N1
C ADIABATIC TOP AND BOTTOM (Y=0,Y=XL)
   T(I,1,K)=T(I,2,K)
   T(I,M1,K)=T(I,M2,K)
 866 CONTINUE
    RETURN
C
    ENTRY PRTOUT
   IF(ITER.NE.0) GO TO 400
   PRINT 401
 401 FORMAT (1X,'SIMPLER',//)
   ANUCLD=0.0
 400 CONTINUE
COMPUTE AVERAGE NUSSELT NUMBER
```

```
      ANUHOT=0.0
      ANUCLD=0.0
      ACHPT=0.
      ACHPS=0.
      ACHPST=0.
      ACHPSB=0.
      ACHPB=0.
      ASUB=0.
      ASUBB=0.
      AGAP=0.
      HTCAP=0.0
      HTCAP1=0.0
C CONTRIBUTIONS TO HOT WALL NUSSELT NO. FROM SIDES OF CHIP
      DO 665 I=3,9
      IF(I.GT.3 .AND. I.LT.9) RRT=RP
      IF(I.EQ.9) RRT=RL
C CONTRIBUTIONS FROM Y-SIDES OF CHIP
       DO 663 K=11,18
      IF(I.EQ.3) THEN
       IF(IMAT(I,10,K).EQ.5) THEN

        AGAP=AGAP+2.*(T(I,10,K)-T(I,9,K))*XCV(I)*ZCV(K)/
     1       ((YCV(10)/RG+YCV(9)))
       ELSE
        AGAP=AGAP+2.*(T(I,10,K)-T(I,9,K))*XCV(I)*ZCV(K)/
     1       ((YCV(10)+YCV(9)))
       ENDIF
       IF(IMAT(I,17,K).EQ.5) THEN
        AGAP=AGAP+2.*(T(I,17,K)-T(I,18,K))*XCV(I)*ZCV(K)/
     1       ((YCV(17)/RG+YCV(18)))
       ELSE
        AGAP=AGAP+2.*(T(I,17,K)-T(I,18,K))*XCV(I)*ZCV(K)/
     1       ((YCV(17)+YCV(18)))
       ENDIF
      ELSE
       ACHPSB=ACHPSB+2.*(T(I,10,K)-T(I,9,K))*XCV(I)*ZCV(K)/
     1      ((YCV(10)/RRT+YCV(9)))
       ACHPST=ACHPST+2.*(T(I,17,K)-T(I,18,K))*XCV(I)*ZCV(K)/
     1      ((YCV(17)/RRT+YCV(18)))
      ENDIF
663   CONTINUE
C CONTRIBUTIONS FORM Z-SIDES OF CHIP
       DO 664 J=10,17
      IF(I.EQ.3) THEN
       IF(IMAT(I,J,11).EQ.5) THEN
       AGAP =AGAP +2.*(T(I,J,11)-T(I,J,10))*YCV(J)*XCV(I)/
     1       ((ZCV(11)/RG+ZCV(10)))
       ELSE
       AGAP =AGAP +2.*(T(I,J,10)-T(I,J,9))*YCV(J)*XCV(I)/
     1       ((ZCV(11)+ZCV(10)))
       ENDIF
```

```
  IF(IMAT(I,J,18).EQ.5) THEN
   AGAP=AGAP+ 2.*(T(I,J,18)-T(I,J,19))*YCV(J)*XCV(I)/
   1       ((ZCV(18)/RG+ZCV(19)))
  ELSE
   AGAP=AGAP+ 2.*(T(I,J,18)-T(I,J,19))*YCV(J)*XCV(I)/
   1       ((ZCV(18)+ZCV(19)))
  ENDIF
 ELSE
  ACHPS =ACHPS +2.*(T(I,J,11)-T(I,J,10))*YCV(J)*XCV(I)/
   1     ((ZCV(11)/RRT+ZCV(10)))
   2            +2.*(T(I,J,18)-T(I,J,19))*YCV(J)*XCV(I)/
   1     ((ZCV(18)/RRT+ZCV(19)))
 ENDIF
664   CONTINUE
665  CONTINUE
    ANUHOT=ANUHOT+ACHPS+ACHPST+ACHPSB+AGAP
    DO 666 J=2,M2
    DO 667 K=2,N2
    DO 669 I=2,M2
     IF(IMAT(I,J,K).NE.0) THEN
HTCAP1=HTCAP1+RHO(I,J,K)*XCV(I)*YCV(J)*ZCV(K)*
   1  (T(I,J,K)-T0(I,J,K))/DT*(PR*RA)**0.5
     ENDIF
     HTCAP=HTCAP+RHO(I,J,K)*XCV(I)*YCV(J)*ZCV(K)*
   1  (T(I,J,K)-T0(I,J,K))/DT*(PR*RA)**0.5
 669  CONTINUE
COMPUTE AVERAGE NUSSELT NUMBER AT THE HOT AND COLD WALL
IF(IMAT(4,J,K).EQ.0) THEN
C  CONTRIBUTION TO HOT WALL NUSSELT NUMBER FROM SUBSTRATE HEAT LOSS
 ANUHOT=ANUHOT+2.*(T(2,J,K)-T(3,J,K))*YCV(J)*ZCV(K)/
   1     ((XCV(2)/RS+XCV(3)))
 ASUB  =ASUB  +2.*(T(2,J,K)-T(3,J,K))*YCV(J)*ZCV(K)/
   1     ((XCV(2)/RS+XCV(3)))
ELSE
C  CONTRIBUTION FORM TOP OF CHIP
 ANUHOT=ANUHOT+2.*(T(9,J,K)-T(10,J,K))*YCV(J)*ZCV(K)/
   1     ((XCV(9)/RL+XCV(10)))
 ACHPT =ACHPT +2.*(T(9,J,K)-T(10,J,K))*YCV(J)*ZCV(K)/
   1     ((XCV(9)/RL+XCV(10)))
C
 IF(IMAT(3,J,K).EQ.5) THEN
   RRT=RG/RC
   RRT1=RG/RS
 ELSE
   RRT=1/RC
   RRT1=1/RS
 ENDIF
C
 ACHPB =ACHPB +2.*RC*(T(4,J,K)-T(3,J,K))*YCV(J)*ZCV(K)/
   1     ((XCV(4)+XCV(3)/RRT))
 ASUBB =ASUBB +2.*RS*(T(3,J,K)-T(2,J,K))*YCV(J)*ZCV(K)/
```

```
  1   ((XCV(3)/RRT1+XCV(2)))
ENDIF
   ANUCLD=ANUCLD+(T(L2,J,K)-T(L1,J,K))*YCV(J)*ZCV(K)/
   1  (XDIF(L1))
667  CONTINUE
666  CONTINUE
c print*,'ANUHOT',ANUHOT
C    ANUHOT=ANUHOT
C  MONITOR SSUM,SMAX AND OTHER QUANTITES AS ITERATIONS PROCEED
C  ON CONVERGENCE, SMAX SHOULD BE VERY SMALL (LESS THAN 1.0E-04)
C  SSUM SHOLD ACHIEVE A SMALL VALUE WITHIN A FEW ITERATIONS, WELL
C  BEFORE CONVERGENCE.  SSUM WILL NOT BE SMALL IF THE BOUNDARY
C  CONDITIONS ARE NOT WRITTEN CORRECTLY.
   XITER=FLOAT(ITER)
c    WRITE(21,*) ITER,T(22,15,15),T(23,15,15),SSUM
   XITER5=FLOAT(ITER/IPR)
   IF(ABS(XITER/FLOAT(IPR)-XITER5).LT.1.E-5) THEN
    IRESID=1
c     PRINT 403,ITER,ITERL,TIME,SSUM,T(6,14,14),V(6,22,14),ENBAL
c     WRITE(12,1121) TIME,ANUHOT,ANUCLD,ASUB,HTCAP,HTCAP1
   ENDIF
 403  FORMAT (I6,I4,5E12.4)
 404  FORMAT (I6,4E12.4)
COMPUTE LOCAL AND GLOBAL NUSSELT NUMBERS AS ITERATIONS PROCEED
   IF( ITER.EQ.250.OR.ITER.EQ.500.OR.ITER.EQ.750
  1.OR.ITER.EQ.1000.OR.ITER.EQ.1250.OR.ITER.EQ.1500
  2.OR.ITER.EQ.1750.OR.ITER.EQ.2000.OR.ITER.EQ.2250
  3.OR.ITER.EQ.2500.OR.ITER.EQ.2750.OR.ITER.EQ.3000
  4.OR.ITER.EQ.3250.OR.ITER.EQ.3500.OR.ITER.EQ.3750
  5.OR.ITER.EQ.4000.OR.ITER.EQ.4250.OR.ITER.EQ.4500
  6.OR.ITER.EQ.4750.OR.ITER.EQ.5000.OR.ITER.EQ.5250
  7.OR.ITER.EQ.5500.OR.ITER.EQ.5750.OR.ITER.EQ.6000
  8.OR.ITER.EQ.6250.OR.ITER.EQ.6500.OR.ITER.EQ.6750
  9.OR.ITER.EQ.7000.OR.ISTOP.GT.0.OR.TIME.GE.TLAST)THEN
    WRITE(8,*)'ITER,RMAX(1),RMAX(2),RMAX(3),RMAX(5)'
    WRITE(8,*)ITER,RMAX(1),RMAX(2),RMAX(3),RMAX(5)
    WRITE(8,*)' V(10,14,14),T(8,14,14),V(6,22,14),T(10,14,14)'
    WRITE(8,*) V(10,14,14),T(8,14,14),V(6,22,14),T(6,22,14)
    WRITE(8,*)'ANUHOT =',ANUHOT,'  HTCAP1=',HTCAP1
    WRITE(8,*)'ANUCLD =',ANUCLD,'  HTCAP=',HTCAP
    WRITE(8,*) ' ACHPS= ',ACHPS,'   ACHPT',ACHPT
    WRITE(8,*) ' ACHPB= ',ACHPB,'  ASUB ',ASUB
    WRITE(8,*) ' ACHPSB= ',ACHPSB,'   ACHPST ',ACHPST
    WRITE(8,*) ' ASUBB= ',ASUBB,'  AGAP ',AGAP
C
   IF(TIME.GE.TLAST.OR.LSTOP) THEN
WRITE(8,*)'RA=',RA,' PR=',PR
WRITE(8,*)'ZL=',ZL, ' RC=',RC
WRITE(8,*)'RS=',RS,' XLHC=',XLHC
   ENDIF
   WRITE(8,*)'***************************************'
```

```
   ENDIF
C
C  CHECK TO SEE WHETHER TO WRITE DATA TO FILE
   IF(TIME.GE.PRTTM(IIPR)) THEN
WRITE(7,*) X,Y,Z,XU,YV,ZW,U,V,W,P,T
IIPR=IIPR+1
WRITE(8,*) ' DATA WRITTEN TO FILE FOR TIME =',TIME
   ENDIF
C
C SEE WHETHER TIMESTEP SHOULD BE LENGTHENED
C
   IF(ITERL.LE.3.AND.ITER.GT.1) THEN
if(time.LE.10.)then
DT=DT*1.5
WRITE(8,*) 'TIME= ',TIME,' TIME STEP CHANGED TO DT =',DT
else
DT=DT*1.1
WRITE(8,*) 'TIME= ',TIME,' TIME STEP CHANGED TO DT =',DT
endif
   ENDIF
C
   IF(TIME.GE.TLAST.OR.ISTOP.GT.0) THEN
C  GET A FIELD PRINTOUT AFTER ITERATIONS STOP
CALL PRINT
C  WRITE IN ORDER TO COMMENCE NEW PROBLEM
WRITE(7,*) X,Y,Z,XU,YV,ZW,U,V,W,P,T
WRITE(8,*) ' DATA WRITTEN TO FILE FOR TIME =',TIME
C  WRITE MATRIX OF CONDUCTIVITIES TO A FILE FOR USE BY PLOT ROUTINE
DO 1122 I=1,L1
DO 1122 J=1,M1
DO 1122 K=1,N1
 IF(IMAT(I,J,K).EQ.-1) THEN
  PC(I,J,K)=RS
 ELSEIF(IMAT(I,J,K).EQ.1) THEN
  PC(I,J,K)=RC
 ELSEIF(IMAT(I,J,K).EQ.2) THEN
  PC(I,J,K)=RP
 ELSEIF(IMAT(I,J,K).EQ.3) THEN
  PC(I,J,K)=RR
 ELSEIF(IMAT(I,J,K).EQ.4) THEN
  PC(I,J,K)=RL
 ELSEIF(IMAT(I,J,K).EQ.5) THEN
  PC(I,J,K)=RG
 ELSEIF(IMAT(I,J,K).EQ.7) THEN
  PC(I,J,K)=RM
 ELSE
  PC(I,J,K)=1
 ENDIF
 1122  CONTINUE
REWIND(9)
WRITE(9,*) PC
```

```
   ENDIF
1121 FORMAT(F13.1,5G13.5)
   RETURN
C************************************************
   ENTRY DIFFUS
   IF (NF.EQ.4) RETURN
   PR=24.0
    RA=1.15e3
    RC=2360.0
    RC=2360.0
    RS=333.0
    RP=266.0
    RL=271.0
    RR=0.42
    RG=796.0
    RM=3900.0

   DO 500 I=1,L1
   DO 500 J=1,M1
   DO 500 K=1,N1
C  DIFFUSIVITY FOR THE U, V OR W EQUATIONS
   IF(IMAT(I,J,K).NE.0) THEN
C  SET DIFFUSIVITY TO A HIGH VALUE FOR ALL SOLID REGIONS
 GAM(I,J,K)=10E15
   ELSE
 GAM(I,J,K)=(PR/RA)**0.5
   ENDIF
C  DIFFUSIVITY FOR THE ENERGY EQUATION
IF (NF.EQ.5) THEN
 IF(IMAT(I,J,K).EQ.-1) THEN
  GAM(I,J,K)=RS/(RA*PR)**0.5
 ELSEIF(IMAT(I,J,K).EQ.1) THEN
  GAM(I,J,K)=RC/(PR*RA)**0.5
 ELSEIF(IMAT(I,J,K).EQ.2) THEN
  GAM(I,J,K)=RP/(PR*RA)**0.5
 ELSEIF(IMAT(I,J,K).EQ.3) THEN
  GAM(I,J,K)=RR/(PR*RA)**0.5
 ELSEIF(IMAT(I,J,K).EQ.4) THEN
  GAM(I,J,K)=RL/(PR*RA)**0.5
 ELSEIF(IMAT(I,J,K).EQ.5) THEN
  GAM(I,J,K)=RG/(PR*RA)**0.5
 ELSEIF(IMAT(I,J,K).EQ.7) THEN
  GAM(I,J,K)=RM/(PR*RA)**0.5
 ELSE
  GAM(I,J,K)=1/(PR*RA)**0.5
 ENDIF
C  SPECIFY ZERO DIFFUSIVITIES FOR THE ADIABATIC BOUNDARIES
  GAM(I,1,K)=0.0
  GAM(I,M1,K)=0.0
  GAM(1,J,K)=0.0
  GAM(I,J,N1)=0.0
```

```
 GAM(I,J,1)=0.0
 ENDIF
 500   CONTINUE
    IF (NF.NE.2 .AND. NF.NE.5) RETURN
C  SOURCE TERMS ARE EVALUATED ONLY FOR INTERIOR POINTS
    DO 501 I=2,L2
    DO 501 J=2,M2
    DO 501 K=2,N2
     IF (NF.EQ.2) THEN
C
C  SOURCE TERM FOR X MOMENTUM
C
C  INTERPOLATE TO GET THE VALUE OF TEMPERATURE AT THE CONTROL
C  VOLUME
C  INTERFACE, SINCE THE VELOCITY U IS EVALUATED AT THE INTERFACE.
TM=FY(J)*T(I,J,K)+FYM(J)*T(I,J-1,K)
CON1=TM
C  SUPPLY ONLY PART OF THE SOURCE TERM IN THE MOMENTUM EQ. TO
C  AVOID
C  DIVERGENCE BEFORE 200 ITERATIONS
CON(I,J,K)=FLOAT(ITER**2)*CON1/200.**2
    IF (ITER.GT.200.OR.IRAMP.EQ.0 )CON(I,J,K)=CON1
C
C  SOURCE TERM FOR ENERGY EQUATION IN SLAB
C
ELSE
      IF(IMAT(I,J,K).EQ.1)THEN
      CON(I,J,K)=1/(PR*RA)**0.5/XLHC/XLLC**2
      ENDIF
     ENDIF
 501   CONTINUE
RETURN
C ************************************************************************
    ENTRY NRGBAL
C
    ANUCLD=0.0
    HTCAP=0.0
    DO 780 J=2,M2
     DO 780 K=2,N2
DO 770 I=2,L2
 HTCAP=HTCAP+RHO(I,J,K)*XCV(I)*YCV(J)*ZCV(K)*
   1   (T(I,J,K)-T0(I,J,K))/DT*(PR*RA)**0.5
 770   CONTINUE
ANUCLD=ANUCLD+(T(L2,J,K)-T(L1,J,K))*YCV(J)*ZCV(K)/
   1    (XDIF(L1))
 780  CONTINUE
C    WRITE(*,*) ' HTCAP =',HTCAP,' ANUCLD =',ANUCLD
c print*,ANUCLD,HTCAP
    ENBAL=ANUCLD+HTCAP-1
    RETURN
END
```

```
 CONTINUE
C    WRITE(*,*) ' HTCAP =',HTCAP,' ANUCLD =',ANUCLD
c print*,ANUCLD,HTCAP
     ENBAL=ANUCLD+HTCAP-1
     RETURN
 END
```

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